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COLLECTED PHYSICAL PAPERS

OF

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WITH 123 ILLUSTRATIONS

LONGMANS, GREEN AND CO.,
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FOREWORD

THIS book contains a collection of the papers on Physical subjects written by Sir Jagadis Bose. A considerable number of these were written some thirty years ago, shortly after the publication of Hertz's experiments on Electric Waves when the study of the properties of electric waves was being pursued with great vigour. This study was facilitated by the method introduced by Bose, of generating electrical waves of shorter wave length than those in general use. By this method he obtained important results on coherence, polarization, double refraction and rotation of the plane of polarization which are described in the papers collected in this volume. In addition to the purely physical papers there are others which describe the beginnings of Sir Jagadis' application of physical methods to the study of living matter, a subject to which most of his work in recent years has been devoted. The papers make very agreeable reading for the author is never dull. Another aspect of these papers is that they mark the dawn of the revival in India, of interest in researches in Physical Science; this which has been so marked a feature of the last thirty years is very largely due to the work and influence of Sir Jagadis Bose.

J. J. THOMSON.

IRMILY LODGE, CAMBRIDGE;
August 16, 1926.

PREFACE

A COLLECTION of papers mainly physical, dating from the year 1895, is published in the present volume. The first object of my inquiry was the optical properties of Electric Waves, brought down to within a few octaves of visible light. In the course of my investigations I was led to the discovery of electric response of non-living matter, such as metals, an account of which was published in 1900 by the International Congress of Science, Paris. The response, like that of living matter, was shown to exhibit fatigue under continuous stimulation, enhancement under chemical stimulants, and permanent abolition under poisons. These results indicated that the response of the more complex and unstable living matter is ultimately the expression of physico-chemical reactions.

My subsequent investigations were directed towards the establishment of the generalisation of the essential unity of physiological mechanism in plant and animal life. The reaction of living tissues, is greatly complicated by the combined effects induced by the fluctuating changes of the environment. This accounts for the complexity of life-movements, which are by no means capricious but are capable of rational explanation by the discovery of the combined action of different factors, the individual reactions to which are unknown to us. The external conditions can be maintained constant for only a short time during which the effect of variation of an individual factor has to be determined. This necessitates special devices for exceptionally high magnification of responsive movements, which otherwise would have been quite imperceptible. The latent period and the velocity of reaction had also to be determined with great accuracy, as also the energy of the incident stimulus.

The difficulties encountered were overcome by the successful employment of various physical methods of high sensibility and accuracy, which will be found of much service in solving not only physiological but physical problems also. A short account of some of these devices, with illustrative examples of their application, will be found towards the end of this book. The *High Magnification Crescograph* instantly records the imperceptible growth, and the variation induced in it under chemical or electrical stimulation. The *Magnetic Crescograph* records movements beyond the highest powers of the microscope, the magnification produced being about 50 million times. The *Resonant Recorder* inscribes time as short as a thousandth part of a second, and enables the most accurate determination of the *latent* or perception period of the plant and the velocity of transmission of excitation. The *Photosynthetic Recorder* automatically imprints on a moving drum, the rate of carbon-assimilation by plants. The *Magnetic Radiometer* enables relative measurement of energy of every ray of the solar spectrum. In conjunction with a special Calorimeter, a very accurate determination has been made of the efficiency of the chlorophyll-apparatus of green plants in storage of solar energy.

J. C. BOSE.

BOSE INSTITUTE, CALCUTTA;
January, 1927.

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COLLECTED PHYSICAL PAPERS

I

ON POLARISATION OF ELECTRIC RAYS BY DOUBLE-REFRACTING CRYSTALS

A beam of ordinary light incident on a crystal of Iceland spar is generally bifurcated after transmission, and the two emergent rays are found polarised in planes at right angles to each other. The object of the present enquiry is to find natural substances which would polarise the transmitted electrical ray. It was thought that the analogy between electric radiation and light would be rendered more complete if the classes of substance which polarise light were also found to polarise the electric ray. The two phenomena may be regarded identical if the same specimen is found to polarise both the luminous and the electric rays.

As the wave length of electrical radiation is very large compared with that of visible light, it may be thought that very large crystals, much larger than what occur in nature, would be required to produce polarisation of the electric ray. I have, however, succeeded in obtaining polarisation effects with crystals of moderate size. This I was able to do by reducing the length of electric waves to about 5 mm. or so.

These experiments show that certain crystals produce double refraction, and that the transmitted beams are polarised. With the help of a rudely constructed apparatus, I was able, last year, to detect traces of these effects. The apparatus has since been improved in detail; it is now possible to detect the polarisation effect with certainty.

The usual optical method of detecting the bi-refringent action of crystals, is to interpose the double refracting structure between two crossed Nicols. The interposition of the crystal generally brightens the dark field. This is known as the depolarising effect, and is regarded as a delicate test for double refracting substances. There is, however, no depolarising action when the principal plane of the crystal coincides with the polarisation planes of either the Polariser or Analyser. The field also remains dark when the optical axis of the crystal is parallel to the incident ray.

A similar method was adopted for experimenting with polarised electric radiation. A parallel electric beam is first polarised by a wire grating. A similar grating acts as an Analyser. The two gratings are crossed, and the crystal to be examined is interposed. The Receiver is a modified form of "Coherer" with its associated voltaic cell and Galvanometer. Brightening of the field is indicated by a throw of the Galvanometer needle.

APPARATUS USED

The following are the different parts of a complete apparatus :—

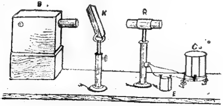

Fig. 1. Polarisation Apparatus.
B, Metallic box enclosing the Ruhmkorff coil and Radiator.
K, The crystal to be examined. E, Voltaic Cell.
C, The Galvanometer. R, tube enclosing sensitive receiver.

Radiator.—Electric oscillation is produced by sparking between hollow hemispheres, and a small interposed sphere. The two beads attached to the hemispheres and the interposed sphere were at first thickly coated with gold, and the surface highly polished. This worked satisfactorily for a time, but after long-continued action, the surface of the ball became roughened, and the discharge ceased to be oscillatory. After some difficulty in obtaining the requisite high temperature, I succeeded in casting a solid ball and two beads of platinum. There is now no difficulty in obtaining an oscillatory discharge; the sparks are made very small, as these are more effective with the receiver used. After a little experience, it is possible to tell whether the discharge is oscillatory or not. The effective sparks have a peculiar smooth sound, whereas non-oscillatory discharges give rise to peculiar cracked sound.

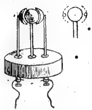

Fig. 2. The Radiator.

As an electric generator, I at first used a small Ruhmkorff coil actuated by a battery. I, however, soon found that the usual vibrating arrangement is a source of trouble; the contact points soon get worn out, and the break becomes irregular. The oscillation produced by a single break is quite sufficient for a single experiment, and it is mere waste to have a series of useless oscillations. But the most serious objection to the production of secondary sparks, unless absolutely wanted, is their deteriorating action on the spark balls.

Anyone who has tried to obtain an oscillatory discharge knows how easily the discharge becomes irregular, and the most fruitful source of trouble is often traced to the disintegration of the sparking surface. In my later apparatus, I have discarded the use of the vibrating interrupter. The coil has also been somewhat modified. A long strip of paraffined paper is taken, and tin-foil pasted on opposite sides; this long roll is wound round the secondary to act as a condenser. In this way there is a great saving of space. The two ends of the primary are in connection with a small storage cell through a tapping key. The coil, a small storage cell, and the key are enclosed in a tin-box; a small opening behind allows the stud of the press-key to pass through. In front of the box there is an opening, through which the radiating tube projects. The radiating box, thus constructed, is very portable. The one I have been using for some time past, is 7 inches in height, 6 inches in length, and 4 inches in breadth. There is another one which is still smaller.

The radiator tube is 2·5 cm. in diameter. As an instance of the efficiency of the radiating apparatus, I may here mention the fact that the storage cell was charged about a month ago; I have since been using the apparatus for electro-magnetic radiation almost every day. All the while it required no attention, and there was no further necessity of polishing the sparking surfaces. To obtain a flash of radiation I have only to press the stud and release it, and on an average, I require about fifty flashes for a day's work. For working an entire month it is therefore only necessary to have a little over a thousand breaks of the primary current. With the usual vibrating interrupter a larger number of breaks would have been necessary even for one hour's work.

Lens for rendering the beam parallel.—In my first apparatus, with the help of an ordinary glass lens and suitable diaphragms, the beam was made approximately parallel. This was more or less a guess-work, as the index of glass for the electric ray has not yet been determined. I have, however, succeeded in determining the electric index for Sulphur, which is very near 1·734. With the knowledge of this index, a cylindrical lens of Sulphur has been constructed, whose focal distance is known with accuracy. The source of radiation, the spark gap, is a line, and the lens is adjusted till its focal line and the spark gap coincide. In this way, a parallel beam of electric radiation is obtained.

Polariser and Analyser.—The success of the experiment depends greatly on the care with which the Polariser and the Analyser are constructed. Fine copper wire, 0·2 mm. in diameter, was carefully wound in parallel lines round two thin sheets of mica; there were about 25 lines in one centimetre. The mica pieces were then immersed in melted paraffin, and the wires thus fixed *in situ*. By cutting round, two circular pieces containing the gratings were obtained. One of these acted as a Polariser and the other as an Analyser.

Receiver.—The receiving circuit consists of a spiral-spring coherer in series with a modified Daniell cell and an aperiodic galvanometer of D'Arsonval type.

In a square piece of ebonite a shallow rectangular depression is cut out, and a single layer of steel spiral springs 2 mm. in diameter and 1 cm. in length is laid side by side, the sensitive surface being 1×2 cm. The springs are prevented from falling by a glass slide in front. The spirals may be compressed by means of a brass piece which slides in and out by the action of a screw. The resistance offered by this portion of the circuit can, therefore, be gradually varied. An electrical current enters along the breadth of the top spiral and leaves by the lowest spiral, having to traverse the intermediate spirals along the numerous points of contact. The resistance of the receiving circuit is thus almost entirely concentrated at the sensitive contact-surface, there being little useless short-circuiting by the mass of the conducting layer. When electric radiation is absorbed by the sensitive contacts, there is a sudden diminution of resistance, and the galvanometer is violently deflected.

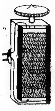
Fig. 3. The Spiral-spring Receiver.

A pair of insulated wires from the ends of the receiver are led out to a galvanometer placed at a distance. The leading wires are shielded from radiation by enclosing them inside two coatings of tin-foil. As an additional precaution, the galvanometer and the voltaic cell are also enclosed in a metallic case with a slit in front of the galvanometer mirror. A spot of light reflected from the mirror is received on a scale. By adjusting the electromotive force of the circuit, the sensitiveness of the receiver may be increased to any extent desirable.

This is most simply effected by the following arrangement of a modified Daniell cell and a shunt. A small

U tube is taken and the two limbs filled with copper sulphate and sulphuric acid, respectively; the bent portion of the tube is plugged with asbestos to prevent rapid mixing of the two liquids. A sliding ebonite piece carries a rod of zinc and a rod of copper, which are plunged in the two electrolytes. The cell is shunted with a resistance of about 10 ohms and the current flowing through the shunt, and therefore the derived E. M. F. is varied by varying the resistance of the cell by raising or lowering the electrodes. When no current is required, the rods are raised out of the liquids. A cell thus constructed is ready for use at a moment's notice, and will work for several days. The receiving circuit does not respond to the incident radiation unless a suitable E. M. F. acts on the circuit. The above simple method of adjusting the proper E. M. F. will be found very simple and effective.

When the Polariser and the Analyser are properly constructed, and the two exactly crossed, no radiation can reach the sensitive surface, and the galvanometer will remain unaffected. The field is then said to be dark. Any slight rotation of either the Polariser or the Analyser partially restores the field, and the galvanometer spot of light then sweeps across the scale.

Method of Experiment

The spark gap of the Radiator is adjusted in a vertical line. The wires of the Polariser are horizontal, and the transmitted electric ray is plane-polarised, its plane of vibration being vertical. The Analyser is now adjusted in a crossed position; on producing a flash of radiation by a single break of the primary, there is no effect on the galvanometer. The crystal to be examined is now interposed with its principal plane inclined at 45° to the horizon.

RHOMBOHEDRAL SYSTEM

(1) *Beryl.*—The first piece experimented on was a large crystal of Beryl. It is a hexagonal prism with basal planes. The specimen examined has each face 11×5 cm. The three axes lying in the same plane are inclined at 60° to each other, the fourth axis, which is also the optical axis, is at right angles to the plane containing the other three. The crystal was optically opaque.

On interposing this block with its principal plane inclined at 45°, the galvanometer spot flew off the scale. The crystal had thus produced the well-known depolarising action. The crystal was now turned round till its principal plane coincided with the vibration plane of the Polariser. There was now no action on the galvanometer. On continuing the rotation, the galvanometer at once responded. The spot became quiescent a second time, when the principal plane coincided with the plane of vibration of the Analyser.

The crystal was now placed with its optical axis parallel to the direction of the incident ray. There was now no action on the galvanometer. Rotation of the crystal round this axis did not produce any effect on the galvanometer. The field continued to be dark.

The piece of Beryl used in the above experiment was unusually large. But in the following experiments the crystals were quite small.

(2) *Apatite.*—In repeating the experiment with this crystal, strongly marked double refraction effect was exhibited.

(3) *Nemalite.*—This is a fibrous variety of Brucite, silky in appearance. In its chemical composition it is a hydrate of magnesia. This specimen exhibited a very strong depolarisation effect with a thickness of less than one cm.

RHOMBIC SYSTEM

Barytes.—A piece of this crystal was found to be strongly double-refracting.

TRICLINIC SYSTEM

Microcline.—This is a greenish blue crystal of the double oblique type. It exhibited polarisation effect in a remarkable degree.

REGULAR SYSTEM

Rock Salt.—A large piece of this crystal did not produce any effect. This is what was expected.

Having satisfied myself of the fact that systems of crystals, other than regular, produce double refraction and consequent polarisation of the electrical ray, I tried the action of electric radiation on crystals ordinarily used in optical apparatus.

I got a fairly large piece of black Tourmaline. On interposing this with its plane inclined at 45°, there was prompt movement of the spot of light. There was no galvanometric indication when the principal plane of the Tourmaline coincided with the vibration planes of either the Polariser or the Analyser.

With ordinary light, a piece of Tourmaline of *sufficient* thickness absorbs the ordinary, but transmits the extraordinary ray. With the piece of Tourmaline used in the last experiment, I found both the rays transmitted, but, it seemed to me, with unequal intensities. In other words, one ray suffers greater absorption than the other. It seems probable that with greater thickness of crystal one ray would be completely absorbed. I found other crystals behaving more or less in the same way. I reserve for another communication particulars of experiments bearing on this subject.

Lastly, I tried an experiment with a crystal of Iceland Spar taken out of a polarising apparatus. With this I got distinct depolarising action.

Summary.—Crystals which do not belong to the Regular System, polarise the electric ray just in the same way as they do a ray of ordinary light. Theoretically, all crystals, with the exception of those belonging to the Regular System, ought to polarise light. But this could not hitherto be verified in the case of opaque crystals. There is now no such difficulty with the electric ray, for all crystals are transparent to it. As a matter of fact, all the above experiments, with one exception, were performed with specimens opaque to light, and it was an interesting phenomenon to observe the restoration of the extinguished electric radiation, itself invisible, by the interposition of what appears to the eye to be a perfectly opaque block of crystal, between the crossed gratings.

(*Asiatic Soc. of Bengal, May* 1895.)

II

ON A NEW ELECTRO-POLARISCOPE

In a paper read before the Asiatic Society of Bengal " On Polarisation of Electric Rays " (May, 1895), I gave an account of some experiments which showed that crystals which do not belong to the Regular System, produce double-refraction of the electric ray, and that the refracted beams are plane-polarised.

Among the numerous crystals examined, I found some exhibiting the so-called depolarising action in a very marked degree, even when the thickness of the crystal was less than the wave-length of the electric radiation. I found, for example, Nemalite, a fibrous variety of Brucite, exhibiting this action with pieces which were comparatively thin. Different varieties of Satin Spar, Serpentine, Tourmaline and a few others were found to be very effective depolarisers.

From the various experiments to be presently described, I was led to suppose that these crystals transmit the ordinary and the extraordinary rays with unequal intensities. It would thus seem possible to quench one of the two rays by absorption, ordinary radiation after transmission through these crystals thus becoming plane-polarised. It should, however, be mentioned here, that crystals as a rule are far more transparent to electric radiation than to ordinary light, and as a consequence greater thickness of crystals would be required for the complete absorption of one of the two rays.

The apparatus with which the following experiments were carried out, consists of a Radiator emitting short electric waves, a cylindrical lens of sulphur for rendering the electric beam parallel, a pair of Analyser and Polariser, and a Receiver for detecting the electric radiation.

Electric oscillation is produced by sparking between two small platinum beads attached to hollow hemispheres and an interposed small platinum sphere (*cf.* fig. 1). The two electrodes are connected with the secondary ends of a modified Ruhmkorff coil. The usual vibrating interrupter was found to be a source of trouble, and was therefore rejected. A flash of radiation consisting of many electric oscillations is sufficient for a single experiment, and this was easily obtained by a sudden break of the primary current. To economise space, the coil was taken out of the supporting condenser box. Long strips of paraffined paper with tin-foil coatings were wound round the coil, and appropriate connections made with the interrupting key. The coil, about three inches in diameter and five inches in height, was placed vertically at one end of a small tinned-iron box, 6×4×7 inches. The metallic box screens the Receiver from electric and magnetic disturbances produced by the making or breaking of the primary current, the electric radiation being transmitted through a tube along the desired direction.

The box also contains a small storage cell and a tapping key, the press button projecting out of the box through a small hole. In front of the box there is a tube one inch in diameter and three inches long. To the inner end of this tube is fixed an ebonite square on which the radiator is mounted.

Polariser, Analyser and the Crystal-holder

At the further end of the tube is placed the Polariser, which may be a grating or any other form of Polariser, to be presently described. By means of a variable diaphragm at the end of the tube, the amount of electric radiation for an individual experiment may be varied.

Next to the Polariser is the crystal-holder, which allows the principal plane of the crystal to be inclined at any azimuth.

The Analyser is similar in construction to the Polariser, and is mounted at the open end of the cell containing the sensitive Receiver, which is a spiral spring coherer, with numerous points of contact.

The resistance of the coherer varies within wide limits. The one I use gives the best result when the resistance is reduced by compression to about 4,000 ohms; the corresponding current circulating round the circuit is then about 10^{-4} ampere. The incident radiation reduces this resistance to 10 ohms or less. The sudden increase of current, due to the diminution of resistance, produces a deflection of the spot of light reflected from the galvanometer.

The coherer is enclosed in a small metallic cell open in front for the reception of the Analyser. The metallic cell has also a tubular projection behind, through which the wires from the ends of the coherer pass out.

Adjustable E. M. F. and the Galvanometer

The wires from the ends of the coherer lead to an adjustable E. M. F. and a dead-beat galvanometer of D'Arsonval type. The wires are placed within a double coating of tin-foil, and the galvanometer and the voltaic cell enclosed in a metallic case with a slit for the passage of the reflected spot of light. These precautions are taken for shielding the receiving circuit from the disturbing action of stray radiations.

The sensitiveness of the Receiver depends greatly on the proper adjustment of the E. M. F. For all-round work, an E. M. F. of about ·45 volt, is best suited with the particular coherer used in my experiments. This was obtained from an Iron-Zinc cell, the Iron being immersed in a solution of ferric chloride, and Zinc in dilute sulphuric acid. After the Receiver has been subjected to radiation for a length of time, its sensibility is diminished; this may be restored by slightly increasing the E. M. F. The Receiver is placed in a derived circuit, the main current, and therefore the derived E. M. F., being varied by means of a rheostat.

Method of experiment

When the spark-gap is vertical, the electric radiation is to a great extent polarised, the vibration being accompanied by electric force in a vertical plane, and magnetic force in a horizontal plane. I shall, for simplicity, consider only the electric vibration. When the partially-polarised radiation is transmitted through a horizontal grating, the emergent beam is completely polarised, the vibration taking place in a vertical plane passing through the axis.

The spiral-spring coherer itself exhibits selective absorption. It absorbs more readily vibrations parallel to its length. Thus, when the spark-gap and the coherer are parallel, the response is very energetic, whereas the response is but feeble when the two are crossed. The analysing action of the coherer becomes more complete if it be further provided with an Analyser grating with wires perpendicular to the length of the coherer.

There are two principal positions of the Polariser and the Analyser:—

(1) *Parallel position.*—When both the gratings are horizontal.

(2) *Crossed position.*—When the polarising and analysing gratings are at right angles to each other.

In the first position, the radiation being transmitted through both the gratings, falls on the sensitive surface, and the galvanometer responds. The field is then said to be bright. In the second position the radiation is extinguished by the crossed gratings, the galvanometer remains unaffected, and the field is said to be dark. But on interposing certain crystals with their principal planes inclined at 45° to the horizon, the field is partially restored, and the galvanometer spot exhibits large deflection. This is the so-called depolarising action of double-refracting substances.

Experiment with Serpentine

I obtained a piece of fibrous Serpentine of greenish colour from the Geological Department of India; its thickness was about 2 cm. I interposed it with its fibres inclined at 45°, between the crossed Polariser and Analyser. There was at once a restoration of the field.

The Polariser and the Analyser were now made parallel, and the piece of Serpentine placed with its fibres vertical or parallel to the vibration of the electric ray; the galvanometer now ceased to respond, proving the complete absorption of the ray by the Serpentine.

The piece of Serpentine was now held with the fibres horizontal, and the radiation was found to be copiously transmitted.

In other words, *Serpentine transmits vibrations perpendicular to the fibres, but absorbs vibrations parallel to the fibres.* Ordinary radiation would thus, after transmission through Serpentine, be plane-polarised, the vibration taking place perpendicular to the fibres. To ensure complete polarisation, the piece should be fairly thick.

An efficient Polariser or Analyser can thus be made of substances like Serpentine, provided that the thickness is sufficiently great.

Satin Spar, Tourmaline and Nemalite

I also found different crystals exhibiting unequal transparency to polarised radiation in different directions. Satin-spar exhibits it, the electric vibration being more easily transmitted across the fibres. I next tried some experiments with a piece of black Tourmaline about 2 cm. in thickness. With this thickness, it was not possible to obtain complete extinction, unless the intensity of the incident radiation was considerably diminished. I at first arranged the Polariser and the Analyser parallel, and the Tourmaline was successively held vertical and horizontal. The Receiver responded with unequal intensities, the response being more energetic *when the length of Tourmaline was parallel to the electric vibration.* With fibrous varieties of crystals, I found the vibration, as a rule, more easily transmitted perpendicular to the length of fibres.

I now held the Tourmaline horizontal, and by varying the aperture at the end of the radiating tube, diminished the amount of radiation, so that at a certain point there was no response in the Receiver. On now holding the Tourmaline vertical, the Receiver at once responded.

I next experimented with a piece of Nemalite. The crystal I used was a very small one, only one cm. in thickness, but this comparatively thin piece exhibited unusually strong depolarising action. It is therefore highly probable that a sufficiently thick piece of Nemalite would make an efficient Polariser.

Experiment with Jute Cell

The most efficient polarising substances I have come across are the vegetable fibres. Among these may be mentioned the fibres of Aloes (Agave), Rhea (Boehmeria nivea), Pine Apple (Ananas sativus), Plantain (Musa paradisiaca).

Common jute (Corchorus capsularis) exhibits the property of polarisation in a very marked degree. I cut fibres of this material about 3 cm. in length, and built with it a cell with all the fibres parallel. I subjected this cell to a strong pressure under a press. I thus obtained a compact cell 3×3 cm. in area, and 5 cm. in thickness. This was mounted in a metallic case, with two openings 2×2 cm. on opposite sides, for the passage of the radiation.

The polarising grating was removed, and the Analyser arranged with its vibration plane vertical. The jute cell was now interposed with its fibres horizontal, and the Receiver was found to respond energetically.

The cell was now placed with the fibres vertical, and there was now not the slightest action on the Receiver.

The fibres were now inclined at 45° to the horizon. There was an immediate response in the Receiver but the radiation was completely extinguished by rotating the Analyser till the grating crossed the fibres. On continuing the rotation, the Receiver responded most when the wires of the grating and the fibres became parallel. Keeping the jute cell fixed at 45°, it was found that during one complete rotation of the Analyser, there were four positions of extinction (when the wires and fibres crossed), and four positions of maximum transmission (when the wires and the fibres were parallel).

From the above experiments, it is quite clear that a jute cell produces complete polarisation of the transmitted ray, the plane of vibration being perpendicular to the fibres.

Two jute cells were then made, and the gratings discarded. One of these acts as a very efficient Polariser, the other as an Analyser. When the two are crossed, the electric radiation is completely extinguished.

In the polarisation apparatus described above, three different types of Polariser (or Analyser) can be used :—

(1) The wire grating Polariser.
(2) Polariser made of crystals like Tourmaline or Nemalite.
(3) Jute or vegetable-fibre Polariser.

The apparatus may also be used as a Polarimeter, the rotation of the Analyser being easily measured by means of the graduated disc.

(The Electrician, Dec. 1895.)

III

ON DOUBLE REFRACTION OF THE ELECTRIC RAY BY A STRAINED DIELECTRIC

The following investigations were undertaken to find whether a solid dielectric becomes double-refracting to the electric ray when it is subjected to a molecular stress by unequal expansion in two directions, or by mechanical compression.

The Electric Polarisation Apparatus, previously described, was used for these experiments. The Analyser and the Polariser were crossed. The strained substance was then introduced between the crossed Analyser and Polariser.

Effect due to unequal expansion

I cast a rectangular piece of paraffin, and chilled its surface unequally by a freezing mixture. On suitably interposing this between the Polariser and the Analyser, the galvanometer spot was at once deflected, proving the double-refracting nature of the strained dielectric. The piece was cast six months ago. It retains its unannealed property even now.

I took two zinc tubes, one cylindrical and the other rectangular, and made castings of melted pitch, which set on cooling. In the cylindrical tube the strain was the same in all directions at right angles to the axis, and this cylindrical mass of pitch did not exhibit any double-refraction. But in the tube with the square section, unequal strain was evident in rectangular directions, perpendicular to the axis; two of the opposite sides bulged out, and the other two bulged in. On interposing this piece between the crossed Polariser and Analyser, it exhibited double-refraction.

Effect due to compression

It appeared that stratified rocks, which, from the nature of their formation, were subjected to great pressure, would serve well for the purpose of this experiment. My anticipations were verified, as the following experiments will show:—

I took a cube of Sandstone, about 5 cm. on each side, and held it between the Polariser and the Analyser, *with the plane of stratification* inclined at 45°. The galvanometer at once responded.

I then rotated the piece of rock, and adjusted it with its *plane of stratification parallel to the vibration plane of the Polariser. There was now no depolarisation effect,* the galvanometer remained unaffected. On further rotation in the same direction, the depolarisation effect re-appeared, to disappear again when the plane of stratification was made parallel to the vibration plane of the Analyser.

Experiments with many other rocks, gave similar result.

(*The Electrician, Dec.* 1895.)

IV

ON THE DETERMINATION OF THE INDEX OF REFRACTION OF SULPHUR FOR THE ELECTRIC RAY

The indices of refraction of transparent substances have been determined by the usual optical methods. There are, however, numerous substances like the various rocks, wood, brick, coal-tar, and others which are not transparent to light, so that their indices could not be determined. These substances are, nevertheless, transparent to electric radiation; the present investigation was therefore undertaken to find a direct method of determining their indices with a high degree of accuracy.

Even in the case of optically transparent substances, the indices are only known for the narrow range of light waves. For greater wave lengths, the index is inferred from Cauchy's formula. Professor Langley has, however, shown that this formula fails to give trustworthy results when applied to the dark radiations in the infra-red region of the spectrum. It does not, therefore, seem at all likely that it will give any reliable results when applied to the electric radiation.

For the determination of the index for the electric ray, the prism method is unsuitable. In the well-known Hertzs' experiment with the pitch prism, the deviation of the refracted rays extended from 11° to 34°. The approximate value of $\mu = 1{\cdot}69$, obtained from this experiment, is probably higher than the true value by about 15 to 20 per cent.

For the accurate measurement of deviation, the effect produced by radiation on the receiver should undergo an abrupt variation. When the radiation passes from an optically denser to a lighter medium, then at a certain critical angle of incidence, the radiation is totally reflected. From the critical angle the index of refraction is easily determined. The great advantage of this method lies in the fact that the transition from refraction to total reflection is very sudden.

I have determined the μ of various substances for the electric ray, by the method of total reflection, which gives very accurate results.

The refracting substance cut out or cast in the form of a semi-cylinder, is mounted on the central table of a spectrometer; the electric ray is directed towards the centre of the spectrometer, and its direction is always kept fixed. It strikes the curved surface and is refracted into the denser medium without any deviation. It is then incident on the plane surface of the semi-cylinder and is refracted into the air beyond.

The incident angle on the plane surface is increased or decreased by rotating the central table on which the cylinder rests. In practice, it is more convenient to commence the experiment with an angle of incidence greater than the critical angle, the incident ray being then totally reflected. The angle of incidence is next slowly decreased till its value is slightly less than the critical. At this point the ray is refracted into the air, making an angle of 90° with the normal to the surface; a receiver fixed against the side of the semi-cylinder at R, responds to the refracted radiation. A slight increase of the angle of incidence produces total reflection and the receiver ceases to respond.

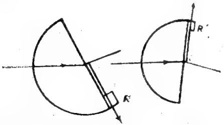

Fig. 4. The refracting semi-cylinder and the Radiator at R and R′.

The platform on which the cylinder rests, carries the usual index. Rotation of the cylinder in a left-handed direction gives a reading for total reflection. A second reading is obtained by rotation of the cylinder in the opposite direction, the receiver being now at R′. The difference between the first and the second reading is evidently equal to twice the critical angle.

A metallic screen with a small central opening is placed against the plane face of the semi-cylinder for utilising only the central rays. In order that all the rays should undergo total reflection simultaneously, it is necessary that the rays incident on the plane of separation of the two media should be parallel. This is effected by the cylinder itself. From the approximate value of μ found from a preliminary experiment, the focal distance of the semi-cylinder is roughly calculated. The spark-gap of the radiator is placed at this focus, and the rays thus rendered nearly parallel. Each subsequent experiment gives a more accurate value of μ, and from the corrected value of the focal distance thus obtained, a more accurate adjustment is made for the next experiment.

Apparatus Used

The apparatus used consists of an electric radiator emitting short waves, a large graduated circle provided with a central circular platform on which the refracting substance is placed, and a receiver, which responds to the electric radiation.

The Radiator.—Electric oscillation is produced by sparking between two metallic beads and an interposed metallic sphere one cm. in diameter. By a single sudden break of the primary in a Ruhmkorff's coil, a flash of radiation is emitted. The spark gap is placed at one end of a brass tube 5 cm. in diameter. By a sliding arrangement, the length of the tube can be varied. The Ruhmkorff's coil is enclosed in a copper box.

The Circle.—The circle has a diameter of 45 cm., and is graduated into degrees, but one-fourth of a degree can be easily estimated. The circle, as a whole, may rotate round a vertical axis which passes through the centre of a massive stand. There is a raised circular platform at the centre of the circle on which the refracting substance is placed. This platform carrying an index, can be rotated independently of the large circle. When the platform index is clamped, the two circles rotate together.

The Refracting Substance.—For substances which can be cast, the molten mass is poured into a cylindrical mould with a thin partition in the middle. In this way two equal semi-cylinders are obtained at each casting. Substances like wood or stone are turned, and the cylinder sawn into two equal halves; In my experiments, different sized cylinders were used; I have successfully used small ones with a radius of 8 cm. only. But when the cost of the material is not prohibitive, it is advisable to use fairly large cylinders. The cylinders used in the following experiments were 27·4 cm. in diameter, and 10 cm. or more in height. For liquids, the cylindrical glass trough used has a diameter of 25 cm.

The tube of the radiator is fixed and points to the centre of the graduated circle. The vertical central line of the cylinder passes through the centre of the circular platform.

The Receiver.—The receiver is a modified form of the coherer. In a rectangular piece of ebonite a narrow groove is cut out. In this groove bits of coiled steel springs are arranged side by side, only one layer deep. In this way a linear receiver is constructed with a sensitive surface 2 cm. in length and 4 mm. in breadth. By means of a screw, the springs may be gradually compressed, reducing the resistance. The coherer is in a circuit with an aperiodic D'Arsonval galvanometer and a copper-iron cell. The galvanometer has a resistance of 300 ohms, and the voltaic cell has an E. M. F. of about 0·45 volt. A Daniell cell is sometimes used, with a resistance box as a shunt; the E. M. F. can thus be adjusted to suit the sensitiveness of the receiver. When the spiral spring coherer is freshly made, it is over-sensitive. On the second day it settles down to a fair condition, though for about half an hour its action is rather unsteady; but afterwards the sensitiveness becomes fairly uniform. It will maintain this state under favourable conditions for nearly an hour, after which it begins to lose its sensitiveness. It must also be borne in mind that the sparking balls also are undergoing deterioration. The sensitiveness of the coherer may be partially restored by slightly raising the E. M. F. of the circuit. In this way it is sometimes possible to work continuously for about two hours; but greater weight should of course be given to the first sets of observations, which are taken at a time when the receiver is most sensitive.

It is superfluous to add that special precautions should be taken to guard against the disturbance due to stray radiations. The walls of the room, the table, even the person of the experimenter himself may act as reflectors, scattering the rays in all directions. I spent a considerable time in trying to find a substance that will act as a good absorber. Lamp black is useless, as it reflects copiously. Blotting paper soaked in water or copper sulphate solution does produce a certain amount of absorption; but even with these a certain amount of reflection is found to take place.

By proper screening, the disturbance due to stray radiations may, however, be got rid of. The radiating apparatus, with the exception of a tubular opening, is completely enclosed in a metallic box. The radiator tube extends right up to the refracting cylinder. The leading wires from the coherer are enclosed in a double coating of tin-foil.

Method of Experiment

I first tried to determine the index of refraction of sulphur. The material used was ordinary commercial sulphur. A semi-cylinder was made, and the two positions for total reflection determined by the method which had already been described. The difference of readings found for the two positions varied from 69° to 71° and the value of the critical angle would from these experiments seem to lie between 34·5° and 35°. This approximate value for the critical angle having been

obtained, the experiment was modified to secure a higher degree of accuracy.

Two equal semi-cylinders P and Q were taken and placed on the rotating table face to face, with an air space between. A metallic plate with a narrow rectangular opening was also interposed between the semi-cylinders to serve as a diaphragm to cut off all but the central rays. When the spark gap is placed at O, the principal focus of P, the rays emerge parallel into the air space, and are then focussed by the second cylinder at an equal distance f on the other side.

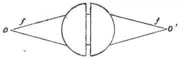

Fig. 5. Two semi-cylinders separated by air-space.

The spark gap is placed at O, and the receiver at O′, OO′ being extremities of a diameter passing through the centre of the circle. The air space is for convenience placed parallel to the index.

The platform carrying the cylinders is now rotated, say to the left. The angle of incidence is thus gradually increased, till the rays just undergo total reflection.

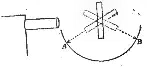

Fig. 6.

(The dotted lines represent the two positions of the air-space for total reflection.)

When this is the case the receiver ceases to respond. Let A be the corresponding reading of the platform index. A stationary index I′ is now placed opposite the reading A of the graduated circle.

When the cylinder is rotated in the opposite direction a second reading B for the critical angle is obtained. It is obvious that, neglecting errors, A—B is equal to twice the critical angle.

The platform index is now clamped and the circle as a whole is rotated till B comes opposite to the fixed index I′. The circle is now clamped, the platform arm unclamped, and the central table rotated till another reading C for the critical angle is obtained. Then, as in the previous case, B—C=2*i*, where *i* is the critical angle. The circle as a whole is now rotated till C comes opposite the fixed index.

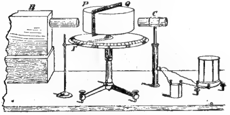

Fig. 7. R, the Radiator; C, the Receiver.

Thus at each successive operation the circle is rotated past the fixed index through 2*i*. The successive difference of readings of the circle in reference to the fixed outside index, thus gives a series of values of 2*i*.

The result will be more accurate if we take the mean readings $\frac{1}{2}(A+B)$, $\frac{1}{2}(B+C)$, …., and take their differences (cf. second and third tables given below). Successive readings are taken till the graduated circle is rotated as near as possible through 360°.

As has been said before, there are two semi-cylinders P and Q. In the first set of experiments P is turned towards the radiator, Q acting as a focussing lens. The circle at each successive operation moves in the *right-handed* direction.

In the second set of experiments Q is turned towards the radiator, P acting as the converging lens. Successive readings are taken as before, the circle now rotating in the *left-handed* direction.

It will be observed that the final results obtained from the two sets are freed from many of the outstanding errors.

I give below the results of two sets of experiments each extending through eleven observations. The receiver was in an unusually good condition for nearly an hour, and during that time I took six observations with P to the front and six more with Q in the same position. As the receiver continued to remain in a fairly responsive condition I took five more for each set. As already said, greater weight should be given to the first two sets of six readings, as being taken under the most favourable conditions.

Successive differences of the mean readings, taken with the cylinders P and Q are given below.

P . .	71	70	70·5	70·5	70·5	70	69·5	69·5	69·5	70	=701
Q . .	70	70	71	71	71	71	71	70	70	69·5	=703·5
										Mean .	=702·25

$$i=\frac{702{\cdot}25}{2\times10}=35{\cdot}11;\ \mu=1{\cdot}738.$$

The following are the readings in degrees for the first six sets of observations with P (a, b) or Q (c. d).

P.

	a.	b.	Mean.	Difference.
1 . .	216	144	188	71
2 . .	144	74	109	70
3 . .	74	4	39	70·5
4 . .	(360)+4	293	328·5	70·5
5 . .	293	223	258	70·5
6 . .	223	152	187·5	
				352·5...... A.

Q.

	c.	d.	Mean.	Difference.
1 . .	308	360+18	343	70
2 . .	18	88	53	70
3 . .	88	158	123	71
4 . .	158	230	194	71
5 . .	230	300	265	70
6 . .	300	360+10	335	
				352·0...... B.

Mean of A and B=352·25.

$$i=\frac{352\cdot25}{2\times5}=35\cdot22\,;\ \mu=1\cdot734.$$

From the results given above it would appear that the index of refraction of sulphur is very near 1·734.

The method is also well suited for liquids; no large quantity of material is required; and the results possess a high degree of accuracy.

The determination of the indices of other solids and liquids are in progress. An account of these will be given in a future communication.

(*Proc. Roy. Soc., Oct.* 1895.)

V

INDEX OF REFRACTION OF GLASS FOR THE ELECTRIC RAY

In my previous paper, read before the Royal Society on October 20, 1895, I described a method of determining the indices of refraction of various substances for electric radiation, the principle of which depends on the determination of the critical angle at which total reflection takes place. A semi-cylinder of the given substance was taken, and the angle of incidence gradually increased till the rays were totally reflected. The experiment was repeated with two semi-cylinders, separated by a parallel air-space. The advantage of the latter arrangement was that the image cast by the two semi-cylinders remained fixed. The image underwent sudden extinction when the angle of incidence attained the critical value.

The determination of the indices of refraction for long electric waves derives additional interest from Maxwell's theoretical relation between the dielectric constant and the refractive index for infinitely long waves. The relation $K=\mu^2$ has, however, been found to be fulfilled in only a few instances. The value μ is usually deduced from Cauchy's formula, which is admittedly faulty when applied to rays below the visible spectrum. It would therefore be of interest to be able to measure *directly* the index for long electric waves, and compare it with the value of K for rapidly alternating electric fields, the periodicity of which is preferably of the same order as that of the electric waves for which the index is determined.

Among the substances in which great divergence is exhibited between the values of K and μ^2, glass may be taken as typical. In the very carefully conducted series of experiments by Hopkinson the value of K (later results) was found to be 6·61 for light flint and 9·81 for extra dense flint glass. He found no variation of K with the time of charge, which varied from 1/4 to 1/20,000 part of a second.[*] Messrs. Romich and Nowak[†] found the value to be 7·5 for alternation of field of about once in a second, while for steady fields they obtained the abnormally high value of 159. Schiller[‡] found K for plate glass to be 6·34, with a frequency of alternation of 25 in a second. With a higher frequency of about $1{\cdot}2\times10^4$, the value obtained was lower, *i.e.*, 5·78. Gordon, with a frequency of $1{\cdot}2\times10^4$, obtained 3·24 as K for common glass.

From the experiments of Schiller it would appear that the value of K for glass diminished with the increase of frequency of alternation of the field.

Rubens and Arons[§] compared the velocities of propagation of electro-magnetic action through air and glass, and obtained the ratio of the velocities or $\mu=2{\cdot}33$. The deduced value of K would therefore be 5·43. M. Blondlot[||] found K to be 2·84 when the frequency of vibration was of the order $2{\cdot}5\times10^7$. Professor J. J. Thomson found the specific inductive capacity of glass to be smaller under rapidly changing fields than in steady ones. He deduced the value of K by measuring the lengths of wave emitted by a parallel plate con-

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[*] Hopkinson, 'Phil. Trans.,' 1881, Part II.

[†] 'Wien. Ber.,' vol. 70, 1874.

[‡] 'Pogg. Ann.,' p. 152, 1874.

[§] 'Wied. Ann.,' vol. 42, p. 581 ; vol. 44, p. 206.

[||] 'Compt. Rend.,' May 11, 1891, p. 1058.

denser with air and glass as dielectrics. The value for glass was found to be 2·7.[*].

On the other hand, Lecher[†] found that the dielectric constant rose with the frequency of vibration. Thus for plate glass—

Frequency.	K.
2	4·64
2×10^3	5·09
$3{\cdot}3\times10^8$	6·50

There is thus a serious difference between the two views of the variation of K (and therefore of μ) with the frequency of vibration. In a previous paper, I alluded to the probability of the variation of μ with the frequency of vibration. The value of μ may at first undergo a diminution with the increase of frequency, reach a minimum, and then have the value augmented when the frequency rises above the critical rate. The result obtained by Lecher is, however, too divergent from the others to be explained by such a supposition.

The direct determination of μ for glass for electric oscillations of high frequency, seemed to me of interest, as throwing some light on the controversy. After the conclusion of my determination of the index for sulphur, I therefore commenced an investigation for the determination of μ for glass. This was, however, greatly delayed by repeated failures to cast glass locally and by my long absence from India. I then obtained from England two semi-cylinders of glass, with a radius=12·5 cm. and height=8 cm.

The method of experiment followed is the same as that described in my previous paper. The radiator is placed at the principal focus (obtained from a preliminary experiment) of one of the semi-cylinders. The cylinder mounted on the platform of a spectrometer is rotated till the rays are totally reflected. From the critical angle the value of μ is deduced.

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[*] 'Roy. Soc. Proc.,' vol. 46, p. 292.

[†] 'Phil. Mag.,' vol. 31, p. 205.

I shall here describe some modifications introduced in the apparatus, which have been found to be great improvements. One of the principal difficulties previously met with was due to the disturbance caused by stray radiation. It is to be remembered that the receiver is extremely sensitive. Comparatively long waves are found to possess very great penetrative power; shielding the receiver then becomes very difficult. Even after the receiver, the galvanometer, and the leading wires had been screened, disturbances were met with which it was difficult to localise. Part of the disturbance may have been due to the magnetic disturbance set up by the generating coil. A double box made of soft iron and thick copper removed this difficulty. But the greatest immunity from disturbance was secured by using short waves. In this case it was not at all necessary to take very special precautions to shield either the galvanometer or the leading wires, the sensitive layer in the receiver being alone affected by the radiation. I exposed the bare leading wires to the strong action of the radiator by putting them in close proximity to the source of radiation, and yet no response was observed in the galvanometer. This freedom from disturbance is not due to the opposite action on the two wires, for a single wire may be exposed to the radiation without any action on the receiver.

With small radiators the intensity of radiation is not very great. This is a positive advantage in many experiments. It sometimes becomes necessary to have greater intensity without the attendant trouble inseparable from too long waves. I have made a new radiator, where the oscillatory discharge takes place between two small circular plates 12 mm. in diameter and an interposed ball of platinum 9·7 mm. in diameter. The sparking takes place at right angles to the circular plates. The intensity of radiation is by this expedient very greatly increased.

In my previous experiments for determination of the index of refraction, I used tubes to surround the radiator. This I was obliged to do to protect the receiver as much as possible from external disturbances. But this procedure may be open to the objection that the sides of the tube may send reflected waves. It is preferable to have a divergent beam from a single source for a well-defined image after refraction. By the successful removal of the disturbing causes it is now possible to allow the radiator to be placed in open space, a plate with a rectangular aperture allowing the radiation to fall on the refracting cylinder along a given direction. The size of the plate is 26×15 cm., and the aperture is 7×6 cm. (see fig. 8). The radiator and the receiver are placed on opposite sides of the plate. Absence of disturbance due to lateral waves was tested by closing the aperture and observing whether the waves still affected the receiver by going round the plate. The plate was found to act as an effective screen.

I have hitherto preferred the null method in my experiments, as it possesses many advantages. The sensitiveness of the receiver can be pushed to the utmost extent, and observations taken when no effect is produced on the receiver. This method of total reflection also dispenses with the difficulty of making accurate measurement of the deviation produced. After obtaining the value of the index by the method described above, I wished to see whether it was not possible to obtain fairly good results by measuring the angle of refraction corresponding to a given angle of incidence. I shall presently describe the difficulties met with in these experiments, and the manner in which they were to a great extent removed.

The preliminary experiment was carried out with a single semi-cylinder. The angle of incidence was gradually increased by rotating the cylinder, and the refracted beam was followed with the receiver. In this way it was found that the rays ceased to be refracted when the angle of incidence was about 28° 30′. The critical angle is therefore 28° 30′ and

$\mu=2{\cdot}08$.................................... (1).

I next used two semi-cylinders. The plane vertical face of the first semi-cylinder was placed along a diameter of the spectrometer circle. The second semi-cylinder was separated from the first by an air-space 2 cm. in breadth. The plane surfaces of the two semi-cylinders were thus separated by a parallel air-space; the first semi-cylinder rendered the beam parallel, and the second focussed the rays on the receiver placed opposite the radiator. With the radiator used, I found a thickness of 2 cm. of air-space to be more than sufficient for total reflection of the incident ray.*

On rotating the cylinders to the right and to the left, two positions for total reflection were obtained. The difference of circle readings for these positions, equal to twice the critical angle, was found to be 58°. The critical angle for glass is therefore 29°.

$\mu=2{\cdot}04$.................................... (2).

Having thus obtained the value of the index, I tried to find whether it would be possible to obtain fairly good results by measuring the deviation of the refracted ray. In the first series of experiments, I used for this purpose a semi-cylinder, with the radiator at its principal focus (the cylindrical surface being next to the radiator), so that the emergent rays were parallel. On trying to find the angle of refraction corresponding to a given angle of incidence, I could obtain no definite reading, as the receiver continued to respond, when moved through five or six degrees on either side of the mean position where the response was strongest. It must be remembered that owing to the finite length of the waves, there is no well-defined geometrical limit to either the ray or the shadow. There is, however, a position for maximum effect, and it is possible with some difficulty so to adjust the sensitiveness of the receiver that it shall only respond to the maximum intensity.

Another troublesome source of uncertainty is due to the action of the tube which encloses the receiver. When a slanting ray strikes the inner edge of the tube, it is reflected and thrown on to the delicate receiver. Unfortunately it is difficult to find a substance which is as absorbent for electric radiation as lamp-black is for light. Lamp-black in the case of electric radiation produces copious reflection. I have tried layers of metallic filings, powdered graphite, and other substances, but they all fail to produce complete absorption,

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* *Vide* the following paper "On the Influence of the Thickness of Air-space on Total Reflection of Electric Radiation."

The only thing which proved tolerably efficient for this purpose was a piece of thick blotting paper or cloth soaked in an electrolyte. A cardboard tube with an inner layer of soaked blotting paper is impervious to electric radiation, and the internal reflection, though not completely removed, is materially reduced. No reliance can, however, be placed on this expedient, when a very sensitive receiver is used.

After repeated trials with different forms of receiving tubes, I found a form, described below, to obviate many of the difficulties. Instead of a continuous receiving tube, I made two doubly inclined shields, and placed them one behind the other, on the radial arm which carries the receiver. The first shield has a tolerably large aperture, the aperture of the second being somewhat smaller. The size of the aperture is determined by the wave-length of radiation used for the experiment. It will be seen from this arrangement, that the rays which are in the direction of the radial arm, can effectively reach the receiver, the slanting rays being successively reflected by the two shields. With this expedient, a great improvement was effected in obtaining a definite reading.

When the deviated rays are convergent, the receiver is simply placed behind the shields, at the focus of the rays. But when the rays are parallel, the use of an objective (placed behind the first shield) gives very satisfactory results. As objectives I used ordinary glass lenses; knowing the index from my experiments, I was able to calculate the focal distance for the electric ray. This is of course very different from the focal distance for the luminous rays. I at first used a lens of 6 cm. electric focal distance, but this did not improve matters sufficiently. I then used one with a longer focus, namely, 13 cm., and this gave much better results.

The receiver used to be previously enclosed in a metallic case, 2 cm. in breadth, with an open front for the reception of radiation. The case was to protect the receiver from stray radiations. But by the new arrangement and improved construction, these disturbances were effectively removed. I therefore discarded the use of the metallic enclosing cell, since the rays which did not actually fall on the sensitive surface might be reflected from the back of the metallic cell and thrown on to the sensitive layer. The layer of spirals, only 1·5 mm. in breadth, is laid on a groove in ebonite (which is transparent); and the linear receiver without any metallic case was placed at the focus of the lens.

I now proceeded to measure the angle of refraction corresponding to a given angle of incidence. In the first series observed, the refraction was from glass to air; the curved surface of the semi-cylinder was turned to the radiator, which was placed at its principal focus. The receiver was mounted on the radial arm with the double shields, and the objective in the manner already described. The reading for refracted rays was taken

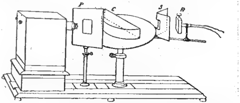

Fig. 8. The electric refractometer: P, the plate with a diaphragm; C, the semi-cylinder of glass; S, the shield (only one shown in the diagram); R, the receiver.

in the following manner. Having adjusted the semi-cylinder for a given angle of incidence, the receiver was moved round till it responded to the refracted ray. Readings were taken first by placing the receiver at an angle less than the true reading and gradually *increasing* the angle till there was a response. The receiver was then placed at a greater angle, and the angle gradually *reduced* till the receiver again responded. In this way a series of readings for a particular angle of incidence was obtained. These readings were found fairly concordant, the maximum variation from the mean being not so great as 1°. One set of readings was taken on one half of the spectrometer circle; the cylinder was next rotated in the opposite direction, and readings taken on the other side.

Angle of Incidence.	Angle of Refraction.			μ.
	Reading to the right.	Reading to the left.	Mean.	
15°	31° 0′ 31 0 31 30 31 30	31° 30′ 30 30 31 30 31 30	31° 15′	2·00
20°	45° 30′ 45 30 44 30 45 30	45° 30′ 46 0 44 0 45 30	45° 15′	2·08
22°	48° 0′ 50 0 49 30 50 0	49° 30′ 50 30 48 30 50 0	49° 30′	2·03

Mean value of $\mu=2{\cdot}04$………… (3).

In the next series of observations, the rays were refracted from air into glass. The electric beam was rendered parallel with the help of a glass lens (f=4 cm.). The beam was incident on the *plane* face of the semi-cylinder. As the cylinder itself focussed the refracted beam, the objective hitherto used in conjunction with the receiver was dispensed with.

i.	*r*.	Mean value of *r*.	μ.
40°	18° 19 18	18° 20′	2·04
50°	22° 23 22° 30′	22° 30′	2·00
65°	25° 30′ 26° 27	26° 10′	2·05

Mean value of $\mu=2{\cdot}03$………… (4).

The different values of μ obtained are given below :—

From total reflection from a single semi-cylinder .	2·08….	(1)
„ „ „ two semi-cylinders .	2·04….	(2)
From refraction from glass into air . . .	2·04….	(3)
„ „ air into glass . . .	2·03….	(4)

The frequency of vibration was of the order 10^{10}.

The value of the index of the glass for sodium light by the total reflection method was found to be

$$\mu_D = 1{\cdot}53.$$

(*Proc. Roy. Soc., Nov.* 1897.)

VI

THE INFLUENCE OF THE THICKNESS OF AIR-SPACE ON TOTAL REFLECTION OF ELECTRIC RADIATION

In my preliminary experiments on the determination of the index of refraction of various substances for electric radiation, I used a single semi-cylinder of the given substance; the electric ray was refracted from the denser medium into air, and at the critical angle of incidence it underwent total reflection. The experiment was repeated with two semi-cylinders separated by a parallel air-space. With light waves, an extremely thin air-film is effective in producing total reflection. But a question might arise whether waves a hundred thousand times as long would be totally reflected by films of air, and, if so, it would be interesting to find out the minimum thickness of air-space which would be effective in producing this result. The factors which are likely to determine the effective thickness of air-space for total reflection are: (1) the index of refraction of the refracting substance; (2) the angle of incidence; and (3) the wave-length of the incident electric radiation. In the following investigation, I have studied the influence of the angle of incidence and of the wave-length in modifying the thickness of the effective air-space. The refracting substance used was glass.

1. *Influence of the Angle of Incidence*

The experimental difficulty in these investigations lies in the fact, that there is at present no receiver for electric radiation which is very sensitive, and at the same time strictly metrical in its indications. The

difficulty is further accentuated by the fact that the intensity of the electric radiation cannot be maintained absolutely constant. Attempts have been made in the following experiments to remove, to a certain extent, some of these difficulties.

Two semi-cylinders of glass, with a radius of 12·5 cm., were placed on the spectrometer circle. The plane faces were separated by a parallel air-space. The radiator was placed at the principal focus of one of the semi-cylinders; the rays emerged into the air-space as a parallel beam, and were focussed by the second semi-cylinder on the receiver placed opposite the radiator. Electric radiation was produced by oscillatory discharge between two small circular plates having a diameter of 1·2 cm. and an interposed platinum ball 0·97 cm. in diameter.

The two semi-cylinders were separated by an air-space 2 cm. in thickness; this thickness was found to be more than sufficient for total reflection. The critical angle for glass I found to be 29°. The experiments were commenced with an angle of incidence of 30° (slightly greater than the critical angle). The receiver, which was placed opposite the radiator, remained unaffected as long as the rays were totally reflected. But on gradually diminishing the thickness of air-space by bringing the second semi-cylinder nearer the first (always maintaining the plane surfaces of the semi-cylinders parallel), a critical thickness was reached when a small portion of the radiation began to be transmitted, the air-space just failing to produce total reflection. The *beginning* of transmission could easily be detected and the critical thickness of air determined with fair accuracy. When the thickness of air was reduced to 14 mm., the receiver began occasionally to be affected, though rather feebly. But when this was reduced to 13 mm. there was no uncertainty; a measurable, though small, portion of the radiation was now found to be always transmitted.

I now increased the angle of incidence to 45°, and observed that the minimum thickness, which at 30° just allowed a small portion of radiation to be transmitted, was not sufficiently small to allow transmission at the increased angle of incidence. The thickness had to be reduced to something between 10·3 mm. and 9·9 mm. for the beginning of transmission.

With an angle of incidence of 60°, the minimum thickness for total reflection was found to lie between 7·6 mm. and 7·2 mm.

Angle of incidence.	Minimum thickness of air for total reflection.
30°	Between 14 and 13 mm.
45	,, 10·3 and 9·9 mm.
60	,, 7·6 and 7·2 mm.

The minimum effective thickness is thus seen to undergo a diminution with the increase of the angle of incidence.

II. *The influence of the Wave-length*

In the following experiments I kept the angle of incidence constant, and varied the wave-length. I used three different radiators, R_1, R_2, and R_3; of these R_1 emitted the longest, and R_3 the shortest waves.

The following method of experimenting was adopted as offering some special advantages. If a cube of glass be interposed between the radiator and the receiver placed opposite to each other, the radiation striking one face perpendicularly would be transmitted across the opposite face without deviation and cause a response in the receiver. If the cube be now cut across a diagonal, two right-angled isosceles prisms will be obtained. If these two prisms were now separated slightly, keeping the two hypotenuses parallel, the incident radiation would be divided into two portions, of which one portion is transmitted, while the other is reflected by the air film in a direction (see fig. 9) at right angles to that of the incident ray, the angle of incidence at the air-space being always 45°. The transmitted and the reflected components would be complementary to each other. When the receiver is placed opposite to the radiator, in the A position, the action on the receiver will be due to the transmitted portion; but when the receiver is placed at 90°, or in the B position, the action on the receiver will be due to the reflected portion. The advantage of this method is that the two observations for transmission and reflection can be successively taken within a short time, during which the sensitiveness of the receiver is not likely to undergo any appreciable change. In practice three readings are taken in succession, the first and the third being taken, say, for transmission and the second for reflection.

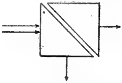

Fig. 9. Section of the two prisms.

I shall now give a general account of the results of the experiments. When the prisms are separated by a thickness of air-space greater than the minimum thickness for total reflection, the rays are totally reflected, there being no response of the receiver in position A, but strong action in position B. As the thickness is gradually decreased below the critical thickness, the rays begin to be transmitted. The transmitted portion goes on increasing with the diminution of the thickness of air-space, there being a corresponding diminution of the reflected component of the radiation. When the thickness of the air-space is reduced to about 0·3 mm., no reflected portion can be detected even when the receiver is made extremely sensitive. The reflected component is thus practically reduced to zero, the radiation being now entirely transmitted; the two prisms, in spite of the breach due to the air-space, are electro-optically continuous. This is the case only when the two prisms are made of the same substance. If the second prism be made of sulphur, or of any other substance which has either a lower or a higher refractive index, then there is always a reflected portion even when the two prisms are in contact.

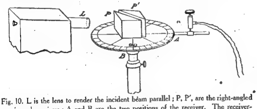

Fig. 10. L is the lens to render the incident beam parallel; P, P′, are the right-angled isosceles prisms; A and B are the two positions of the receiver. The receiver-tube is not shown in the diagram.

Another interesting observation was made by separating the prisms just sufficiently for total reflection. There would now be no transmitted portion. But if a thin piece of cardboard or any other refracting substance were interposed in the air-space, a portion of the radiation was found to be transmitted; it was now necessary to separate the prisms further to reduce the transmitted portion to zero. This method opens out a possibility of determining the electric index of the interposed substance.

Having given a general account of the experiments I shall now describe in detail the method of procedure. The radiator tube was provided with an ordinary lens whose focal distance for electric radiation is about 4 cm. The beam thus rendered approximately parallel fell perpendicularly on the face of the glass prism. The two prisms were made by cutting a cube of glass—an ordinary paper weight—across a diagonal. The size of the cube was 4·5 cm. on each side.* One prism was fixed on the spectrometer circle; the other could be moved so as to change the thickness of the interposed air-space between the two sections very gradually. The separation was simply effected by means of ordinary cards. The cards used were of uniform thickness, each card being 0·45 mm. in thickness. A certain number of cards were taken and placed between the prisms with their surfaces in contact with the hypotenuses. The cards were then carefully withdrawn, leaving the prisms separated by a thickness of air equal to the thickness of the given number of cards. It would, of course, be an improvement to have a micrometer screw by which the thickness can be gradually increased.

* Larger prisms would have been preferred, had they been available. The prisms after cutting were found to be approximately isosceles, the angles being 90°, 46°, and 44°.

Observations were now taken to determine the minimum thickness of air for total reflection for different wave-lengths, the angle of incidence being in all cases kept at 45°. Three radiators, R_1, R_2, R_3, were used. I have not yet made determinations of the lengths of waves emitted by these radiators, but it will be seen from the dimensions of the radiators that the waves emitted by R_1 are the longest and those emitted by R_3 the shortest. The oscillatory discharge in R_1 took place between two circular plates 1·2 cm. in diameter and an interposed ball of platinum 0·97 cm. in diameter. The radiators were enclosed in a tube 3·8 cm. in diameter.

In the radiator R_2, the discharge took place between two beads of platinum and an interposed sphere the same as in R_1. The distance between the sparking surfaces was 1·01 cm.

In the radiator R_3, sparking took place between two beads and an interposed sphere 0·61 cm. in diameter. The distance between the sparking surfaces was 0·76 cm.

One prism was fixed on the spectrometer circle, and the other was at first placed somewhat apart from it; the distance was now gradually reduced till the air-space just ceased to reflect totally, when a small portion of radiation began to be transmitted. The beginning of transmission was detected by the receiver, which was placed in the A position.

Radiator.	Distance between sparking surfaces in mm.	Minimum thickness for total reflection.
R_1	——	Between 10·3 and 9·9 mm....(*a*)
R_2	10·1	" 7·6 and 7·2 mm. ...(*b*)
R_3	7·6	" 5·9 and 5·4 mm. ...(c)

From the above results it is seen that the effective thickness of the totally reflecting air-space increases with the wave-length. If the wave-lengths are proportional to the distance between the sparking surfaces which give rise to the oscillatory discharge, the wave-lengths in (b) and (c) are in the ratio of 101 : 76. This is not very different from the ratio of the corresponding minimum thicknesses of the totally reflecting air-space.

III. *On the Relation between the Reflected and the Transmitted Components of Radiation when the Thickness of Air-space undergoes Variation*

It was stated in the general account of the experiments, that as the thickness of air-space is gradually reduced the intensity of the transmitted portion of radiation is increased, while there is a corresponding diminution of the intensity of the reflected portion. This I have been able to verify qualitatively from numerous observations. But many difficulties are encountered in making quantitative measurements, owing to the difficulty of maintaining the intensity of radiation, as well as the sensitiveness of the receiver, absolutely constant.

As regards the first, the intensity of the emitted radiation depends on the efficiency of the secondary spark, and the nature of the sparking surface. Keeping the primary current that flows through the Ruhmkorff coil constant, the efficacy of the secondary spark is very much affected by the manner in which the contact is broken in the primary circuit. If a vibrating interrupter is used, the break is apt to become irregular; the torrent of the secondary sparks also spoils the sparking surface of the radiator. For merely qualitative experiments the use of a vibrating interrupter is not so very prejudicial, as along with the ineffective discharges there are present some which are oscillatory. But where successive discharges are to give rise to radiation of equal intensity, it becomes necessary to avoid all sources of uncertainty. For these reasons I prefer a single break for the production of a flash of radiation. With some practice it is possible to produce a number of breaks, each of which is effective. If the surface at the break is kept clean, and the break is properly effected, successive flashes of radiation up to a certain number are about equally intense. When the sparking has been taking place for too long a time, the surface no doubt undergoes a deterioration. But twenty or thirty successive sparks are equally efficacious when sparking takes place between platinum surfaces. The use of a single flash of radiation is preferable on another account. The receiver at each adjustment responds to the very first flash, but becomes less sensitive to the subsequent flashes. The conditions of the different experiments are similar, when the action on the receiver is due to a single flash of radiation, instead of the accumulated effect of an unknown number of flashes.

I give below the deflections of the galvanometer produced by four successive flashes of radiation.

(1)	115 divisions.
(2)	122 "
(3)	113 "
(4)	108 "

When very careful adjustments are made, the successive deflections are approximately equal. There are, however, occasional failures, owing either to the fault of the break, or loss of sensitiveness of the receiver.

More serious is the difficulty in connection with the receiver. With the improvements adopted there is no difficulty, under any circumstances, to make the receiver very highly sensitive; but it is not easy to maintain the sensitiveness absolutely uniform. I have in my previous papers explained how the sensitiveness of the receiver depended on the pressure to which the spirals were subjected, and on the E. M. F. acting on the circuit; and how the loss of sensitiveness due to fatigue was counteracted by slightly increasing the E. M. F. For each receiver there is a certain pressure, and a corresponding E. M. F., at which for a given radiation the receiver is fully sensitive. Having obtained these conditions, the sensitiveness can be increased or decreased by a slight variation of either the pressure or the E. M. F. An increase of pressure produced by the advance of the micrometer press screw through a fraction of a millimetre would sometimes double the sensitiveness; similarly an increase of E. M. F. of even $\frac{1}{100}$ volt increases the sensitiveness to a considerable extent.

The nature of the difficulties in maintaining the sensitiveness of the receiver uniform will be understood from what has been said above. But by very careful and tedious adjustments I was however able to obtain fairly satisfactory results, and was in hopes of ultimately obtaining symmetrical values from the galvanometer deflections. The setting-in of the rainy weather has unfortunately introduced other conditions unfavourable to the maintenance of uniformity of the sensitiveness of the receiver. Owing to the excessive damp and heat the spirals get rusty in a short time, and variation in the sensibility is produced by the altered condition of the surface of the sensitive layer. The results of certain experiments I have carried out lead me to hope that this difficulty will, to a certain extent, be removed by covering the sensitive surface with a less oxidisable coating.

The deflections produced in the galvanometer can only be taken as approximately proportional to the intensity of the absorbed radiation. It would be better to observe the diminution of the resistance produced by the incident radiation. This may be done with the help of a differential galvanometer and a balancing resistance.

G is a high resistance differential galvanometer, with two sets of electrodes, A, B; C, D; one pair of electrodes is in series with the receiver, and the other with a resistance box. When the receiver is adjusted to respond to the electric radiation, a weak current flows through it. The same E. M. F. acts on both the circuits. The compensating current, produced by a proper adjustment of the resistance of the box, brings the spot of light back to zero. The resistance of the box is equal or proportional to the resistance of the receiver.

When radiation is absorbed by the receiver the resistance is decreased, and this diminution of the resistance is found from the new balancing resistance.

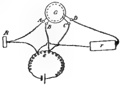

Fig. 11. G, the differential galvanometer ; R, the receiver ; r, the resistance box.

All observations agreed in showing that as the thickness of air-space was gradually decreased, the transmitted component was increased, with a corresponding decrease of the reflected portion. I give below two sets of observations, in which the receiver acted better than usual.

Radiator R_2; distance between the sparking surfaces=10·1 mm.

Thickness of air-space in terms of number of cards.	Thickness in mm.	Galvanometer deflection due to the reflected portion.	Galvanometer deflection due to the transmitted portion.
1	0·45	0 or very slight.	Against the stop.
2	0·90	Slight	,, ,,
4	1·8	80	160
8	3·6	145	150
10	4·5	150	120
12	5·4	160	100
16	7·2	Against the stop	30
18	8·1	,, ,,	0

It is seen from the above, that as the thickness of the air-space was gradually increased, the reflected component increased, while the transmitted portion decreased. The minimum thickness for total reflection was found to be about 8 mm. When the thickness of air-space was reduced to about half this thickness (slightly less than half) the reflected and the transmitted portions seemed to be about equal.

With the radiator R_1 the minimum thickness for total reflection was found to be equal to the thickness of 22 cards (9·9 mm.). When the thickness of air-space was reduced to the thickness of 10 cards (4·5 mm.) the reflected and the transmitted portions seemed to be about equal. As two experiments immediately following each other are more likely to be comparable, the experiments were so arranged that the observation of deflection for *transmission* with a certain thickness of air followed the observation for *reflection* with a different thickness, the corresponding deflections being about equal. As stated above, the reflected and the transmitted portions were approximately equal when the thickness of air was equal to the thickness of 10 cards. Keeping 10 as the mean, pairs of readings were taken with different thicknesses. For example, the reflection reading with a thickness of air equal to the thickness of 4 cards was followed by taking a reading for transmission, with a thickness of air equal to the thickness of 16 cards; the deflections produced in the two cases were about equal, namely sixty-six divisions of the scale.

I append below a table showing the corresponding thicknesses of air (in terms of number of cards) which gave approximately equal deflections, the deflection in one case being due to the reflected component, and in

the other case to the transmitted component. The receiver was made moderately sensitive, so that the deflections lay within the scale.

Thickness of air for reflection.	Thickness of air for transmission.	Deflection produced.
4	16	66
6	14	70
8	12	90
10	10	120

When the thickness of air was reduced to 0·45 mm., a deflection of two divisions was obtained for the reflection reading. From this an approximate idea of the intensity of the reflected component may be obtained. From the table given above, it is seen that half the total radiation gave a deflection of 120 divisions. The intensity of the reflected component, with a thickness of 0·45 mm., is therefore 1/120th part of the total amount of incident radiation, on the assumption, which is only approximate, that the galvanometer deflections were symmetrical. When the thickness was reduced to 0·3 mm., no reflected component could be detected, though the receiver was made extremely sensitive.

(*Proc. Roy. Soc., Nov.* 1897.)

VII

A SIMPLE AND ACCURATE METHOD OF DETERMINATION OF INDEX OF REFRACTION FOR LIGHT

The apparatus usually employed for the determination of the index of refraction is very elaborate and costly. Numerous adjustments have to be made, and a long time spent to secure accurate results. The following method for the determination of the optical index is a modification of the one which has for some time been employed by me in the determination of the index of electric refraction. The apparatus required is very simple, and I made a rough model of it at a trifling cost, and gave it to my pupils for trial. I was surprised to find how, even in their inexperienced hands, it gave results which would compare favourably with the various determinations of the indices hitherto made. The other advantages of this method are the quickness with which a determination can be made, and its adaptability to lecture demonstrations.

The method depends on the determination of the critical angle at which total reflection takes place. The principle of total reflection has also been employed by M. M. Terquem and Trannin, but the method described below is somewhat different, being much simpler, as no Collimator and observing Telescope are required. It has the additional advantage of being applicable to solids; and by a process of repetition, the value of the critical angle is obtained with a remarkably high degree of accuracy.

A beam of light is refracted from the given substance into air, and the angle of incidence gradually increased till total reflection just takes place. From the critical angle i thus determined, the index is found from the formula $\mu = \frac{1}{\text{Sin } i}$.

The necessary appliances for the determination are: (1) a hollow glass cylinder, which may be a beaker, for liquids (or a stoppered phial for volatile substances), or two semi-cylinders of the given solid; (2) a circular wooden table graduated into degrees and capable of rotation round a vertical axis. The table has at the centre a raised circular platform carrying an index. The platform can revolve round the common vertical axis independently of the table. When the platform is clamped down, the circle and the platform revolve together round a common axis.

The apparatus may be used for the following investigations :—

(1) Determination of the indices of solids and liquids.

(2) Variation of the index with the strength of different solutions.

(3) Variation of the index with temperature.

(4) Determination of the indices for the different rays, and of the dispersive power.

1. DETERMINATION OF THE INDEX FOR LIQUIDS

A vertical rectangular plate is suspended so as to divide the liquid in the glass cylinder into two halves. A narrow central and vertical slit is cut in the rectangular plate. Two thin microscope cover slips about one cm. square are superposed and cemented with an interposed air-film, and the piece is fixed against, say, the lower portion of the vertical slit. The liquid is, of course, continuous through the upper and uncovered portion of the slit; but, in the lower portion, the air-film separates the two semi-cylinders of liquid. Light passing through one of these semi-cylinders is thus incident on the second medium, the film of air, and when the angle of incidence is sufficiently large, the beam undergoes total reflection. In order that all the rays might undergo total reflection simultaneously, it is necessary that the incident beam should be parallel.

Adjustment for rendering the beam parallel.—The diagram represents a section of the liquid semi-cylinders: the one to the left we shall call P, that to the right Q.

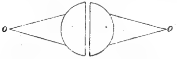

Fig. 12. The source of light O and its image at O^1.

Suppose O to be the principal focus of P; light diverging from a source O, would emerge into the air-film as a parallel beam, and would be focussed by Q at an equal distance, O′ to the right of the air-film. This will be all the more exact if a narrow diaphragm cut off all but the central rays. To render the beam incident on the air-film parallel, it is therefore only necessary to bring gradually the source of light near the cylinder, till an image is formed at an equal distance on the other side, the distances being measured from the axis of the cylinder. It will be observed that the semi-cylinder

P acts as a collimating lens, and Q as the object-glass of an observing telescope. It will also be seen that the value of the index may now be obtained with fair accuracy from the distance OO′ (which is equal to four times the focal distance of the cylinder) and the radius of the cylinder.

As the lens is cylindrical, the source of light may be a line instead of a point. A narrow slit may be illuminated by sodium light for monochromatic measurements; or the slit may be illuminated by sun-light. It is sometimes more convenient to use the incandescent filament of a glow lamp as the source of light.

Method of experiment.—The cylinder containing the liquid with the interposed air-film is placed on the platform, the axis of the cylinder passing through the axis of the graduated circle. If the cylinder is kept fixed, and the direction of incident light changed, it will be observed that there are four positions, A, B, C, D, for total reflection, the angles AOB or DOC being each equal to twice the critical angle.

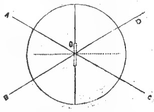

Fig. 13. Four positions for Total Reflection.

The source of light may be kept fixed, and the angle of incidence varied by rotating the central platform on which the cylinder with the interposed film is placed, till total reflection just takes place. The image produced remains fixed, till at the critical angle it suddenly disappears from the screen; this is a great advantage, as the trouble entailed in following the deflected image in the prism-method is avoided. As the cylinder revolves round, total reflection will take place four times, twice from the air-film surface of each semi-cylinder. The source of light and a screen being now fixed at the extremities of a diameter passing through the centre of the circle, the distance of the slit is adjusted for rendering the beam incident on the air-film parallel, in the manner already described. When the angle of incidence reaches the critical value, the image on the screen is suddenly extinguished. In the centre of the screen there is a circular aperture, behind which the eye itself may be placed to receive the light directly. When white light is used, as in the determination of the indices for the different rays, the image is cast on the slit of a small direct vision spectroscope, and the spectrum observed.

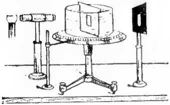

Fig. 14. The Spectrometer circle. There is a sliding tube with a slit at one end. The distance of the slit from the centre of the cylinder is adjusted till a sharp image is formed at an equal distance on the screen to the right. A vertical plate with a slit and air-film is suspended dividing the cylinder in two halves.

A portion of light may be allowed to pass through the upper part of the slit, where the liquid is continuous, and the corresponding portion of the image will never

be extinguished. This portion of the image is used in lecture demonstrations as a marked line of reference. But in the lower portion of the image, light has to pass through the air-film, and the bright image suddenly disappears from the screen as soon as the angle of incidence exceeds the critical value.

During a complete rotation of the cylinder, two pairs of readings will be obtained for total reflection. In the first set, one-half of the semi-cylinder will act as the collimating lens, the other half acting as the focussing lens : in the next set (when the cylinder is rotated through 180°) the functions of the two halves are exchanged. From the mean of the differences obtained from the two sets of observations, the value of $2i$ is obtained with great accuracy, provided the circle is accurately graduated, and the reading Vernier permits of small angular measurements being made.

The circle used in the simple form of apparatus being only divided into degrees, I could not expect to obtain from it, in the ordinary way, any very accurate results; but by using the following method, it was possible to obtain results which are highly accurate.

The platform index is at first clamped down pointing to the zero of the scale, and the circle as a whole rotated till total reflection takes place. The circle is next clamped, and the platform carrying the cylinder unclamped and rotated in the direction of the lower arrow till light is again totally reflected, the

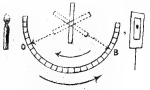

Fig. 15. The dotted lines represent the two positions of the air-film for total reflection.

index reading being now B. The difference of the two readings evidently gives twice the critical angle. The angle is repeated by clamping down the index and rotating the circle as a whole for total reflection in the direction of the upper arrow. The process may thus be repeated, the rotation of the platform in one direction being followed by the rotation of the circle in an opposite direction. There is thus produced at each operation a relative displacement of the index (in reference to the circle) through twice the critical angle. The value of i is by this means obtained with great accuracy, the errors due to eccentricity or defect in graduation being eliminated by repeating the angles n times where $2\ ni$ is as near as possible equal to four right angles or any multiple of four right angles. If R be the difference between the first (zero) and the last readings, the critical angle $i = \frac{R}{2\,n}$. It is evident that by merely increasing n, the value of i could be obtained with any degree of accuracy, even with circles graduated only into degrees.

The index is fixed at the beginning against the zero of scale. It is therefore only necessary to take *one* final reading, and count the number of repetitions. A complete determination could thus be made in the course of a few minutes.

The air-film, as has been said before, should be placed in the vertical plane dividing the cylinder into two halves. This is more easily accomplished by *suspending* a metallic plate on knife edges, from V grooves cut at the ends of a diameter of the upper end of the cylinder. The plate remains vertical under the action of gravity. A central slit is cut in this plate; on opposite sides of this central diaphragm are cemented, as previously stated, the two glass slips which contain the air-film.

One set of readings having been obtained with the semi-cylinder P turned towards the source of light, the cylinder is turned round through 180°, and observation repeated with Q occupying the previous position of P; it will be seen that by this procedure the air-film is also reversed. The mean value of the critical angle obtained from the two sets of observations, one "direct," the other "reverse," is thus free from any outstanding error.

Having explained the principle of measurement, I now proceed to give an account of the experiments, and compare the result obtained by this method with those obtained by previous observers. The values for carbon disulphide, absolute alcohol, glycerine have been determined, but the results obtained by different observers do not agree. The reason for this discrepancy is obvious; it is almost impossible to obtain two different specimens of these substances exactly alike. The only substance which can be obtained in a state of approximate purity is distilled water, but even here we have various contaminations by the absorption of different gases like ammonia and carbonic acid from the atmosphere; or glass itself may be dissolved in minute quantities. The values of the index for water obtained by different observers are therefore not very concordant. The following are the values of the index of water for the D ray :—

Wollaston and Brewster, D ray (temp. not given)	1·336
Sir John Herschel (at density of 1) . .	1·3336

The following are for the D ray at a temperature of 18° :—

Terquem and Trannin	1·3336
Gladstone and Dale (reduced to 18°)	1·3322

If we reject the first two values as somewhat indefinite and take the last two, we find a difference of more than 1 part in a thousand, Gladstone and Dale's result being the lower.

With C ray at the temperature 18° :—

Fraunhofer	1·3317
Gladstone and Dale (reduced to 18°)	1·3304

Here also the same difference is observed. Thus the minimum difference between the best observations is about 1 part in a thousand.

My determinations were made with ordinary distilled water, condensed by passing steam through a coil of copper immersed in cold water. The experiments were carried out with the two following apparatus :—

I. A large circle, roughly graduated into degrees, with a diameter of 45 cm.; the glass trough used is 25 cm. in diameter.

II. The circle was obtained from an old theodolite. The Vernier reads to 1′. The glass cylinder used has a diameter of 14·4 cm.

It must be remarked here that the cylinders at my disposal, though circular in section, were slightly conical in shape. I tried to obviate this defect by using a very small portion of the height of the cylinder for light to pass through, the length of the slit being reduced to about 5 mm.

Just before total reflection, a series of images of the slit are seen reflected by the air-film. When white light

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is used, and the image is observed through a direct vision spectroscope, interference bands are observed in the spectrum, which flit across it with the slightest rotation of the cylinder.

I give below the results obtained from determinations made on different days (temp. = 26°).

(1) The larger apparatus was used for this experiment (diameter of the cylinder = 25 cm.), and the angle repeated fifteen times.

(2) Experiment with the smaller apparatus (diameter of the cylinder = 14·4 cm.). Reading was only taken of two successive positions for total reflection with the air-film 'direct' and 'reverse.'

(3) The same as above but with a different air-film.

(1) Angle repeated fifteen times.

Direct.	Reverse.
1459°	1460°

$$\text{Mean value for } i = \frac{1459{\cdot}5}{2\times 15} = 48^\circ\ 39'$$

$$\mu = 1{\cdot}3321.$$

From (2) and (3), mean value of i obtained $= 48^\circ\ 40'$.

$$\mu = 1{\cdot}3317.$$

The values of μ from the best determinations reduced to the temp. 26° are given below :—

Gladstone and Dale	1·3315
Terquem and Trannin	1·3329

The result obtained by me is thus seen to be practically the same as the above.

Having obtained the absolute value of the index of water for the D line and at the temperature of 26°, the following investigations were made to study the effect of different strengths of solution, of temperature, and of different rays in the variation of the index.

It must be remembered that we are concerned here in measurement of effect of small variations from the standard. The absolute value of the index under the changed condition is deduced from the value under standard condition and the small observed variation.

2. VARIATION OF THE INDEX WITH DIFFERENT STRENGTHS OF SOLUTION

The apparatus is first adjusted for total reflection with distilled water. To the distilled water in the cylinder is added enough salt (*e.g.*, sodium chloride) to make, say, a five per cent. solution. This produces an increase of refractive power, and the angle of incidence has to be decreased to reach the critical angle. The *difference* of the two readings subtracted from the critical angle for distilled water (obtained from a previous accurate determination) gives the critical angle for five per cent. solution, and hence the absolute index. It is to be noticed here that a large number of determinations can be made rapidly by merely adding requisite quantities of salt and taking the corresponding readings.

With a finely-graduated circle, provided with a Vernier, the differences of readings may easily be obtained. With a roughly-graduated scale, the angular differences may be determined by fixing a mirror over the upper portion of the slit, and measuring the small differences in the usual way, by observing a reflected scale through a telescope, or receiving the reflected

spot on a scale. A curve of variation of the indices with the different strengths of solution may thus be easily obtained.

3. EFFECT OF TEMPERATURE

The index of a liquid is increased and the critical angle decreased with the lowering of temperature. Hot water is poured into the cylinder, and the cylinder rotated till the angle of incidence is just a little less than the critical angle for the particular temperature. The liquid is stirred at intervals, and a thermometer bulb placed in the same horizontal layer of the liquid through which light is passing. As the liquid slowly cools down, the critical angle is decreased, and at a certain temperature the image suddenly disappears. The corresponding temperature of the liquid is now observed. The angle is then decreased by a small known amount, and the new temperature for total reflection again observed. In this way the slight variation of the angle with the variation of temperature is found. The absolute value of the critical angle for a standard temperature is known from a previous experiment. Hence the indices for different temperatures may be easily deduced.

4. ON THE DETERMINATION OF THE INDICES FOR THE DIFFERENT RAYS AND THE DISPERSIVE POWER

The value for the D line having been accurately determined by the method of repetition, the values for the other rays are found in the following way :—

Sunlight may be used for the experiment; the image falls on the slit of a direct vision spectroscope. A spectrum is thus formed, in which the well-known Fraunhofer's lines are present. As the cylinder is rotated, a shadow gradually moves along the spectrum, beginning with the most refrangible end. The shadow is made to coincide with the different absorption lines, and the differences between these readings and the " D " reading give the absolute critical angles for the different rays. In this way, the values of the indices for different rays are found, and hence the dispersive power. A greater degree of accuracy is obtained by repeating the difference.

The incandescent filament of a glow lamp may also be used as a source of light. The micrometer in the eye-piece of the spectroscope should have been previously calibrated.

The following determination was made to find the difference between D and F lines. This was repeated ten times, which gave a total difference of 2° 5′. The critical angle for the F ray is therefore less than the angle for D ray by 12·5′. Hence taking the mean critical angle for D to be 48° 39·5′.

μ for D=1·3319.
μ for F =1·3362.

The difference between D and F, as found by me, is therefore about	43 parts in 13,000 at 26°.
Gladstone and Dale found a difference of	42 ,, ,, ,, at 15°.
This difference will, however, be reduced to about . .	41 ,, ,, ,, at 26°.

Indices for solids.—The method for the determination of the indices for solids is precisely the same as that for liquids. The solids are cut in the form of two small semi-cylinders, a process which is not so difficult as the cutting of a prism.

LECTURE DEMONSTRATION

A few words may now be said about the modification of the above for lecture demonstrations. As only a moderate degree of accuracy is required, the source of light (a slit illuminated with sunlight, or any other powerful source) is brought slightly nearer the cylinder, so that the image is cast on a distant screen.

Effect of temperature.—Half the height of the cylinder is filled with cold liquid a circular piece of mica being placed above. Hot liquid is now slowly and cautiously poured over mica. When the cylinder is rotated, the light from the lower half would be the first to undergo total reflection, and this totally-reflected image may be received on a second suitably-placed screen. Light would, however, be still transmitted through the hot portion of the liquid. There would thus be a transference of one-half of the image from one screen to the other. On further rotation the missing portion would join its other half on the second screen. A slight rotation in one direction or the other would produce corresponding transference of the images from one screen to the other.

Different indices for the different rays.—A spectrum is formed by allowing light which forms the image to pass through a carbon bisulphide prism. As the rotation of the cylinder is continued, different portions of the spectrum would be totally reflected in succession, and would appear on the second screen, the spectra on the two screens being complementary.

Conclusion.—My object has been to get a fairly accurate determination of the index and its variations with an improvised and inexpensive apparatus, which can easily be set up. Even with the simple apparatus described above, the quantitative results obtained were shown to possess great accuracy. The determinations were found to be capable of being made with considerable rapidity. Only one final reading was all that was necessary for the determination of the absolute index. With a finely graduated circle, a true cylinder, and a perfectly parallel air-film, there is no reason why the method described above should not give results possessing the highest degree of accuracy.

(From unpublished Paper, 1895.)

VIII

ON THE SELECTIVE CONDUCTIVITY EXHIBITED BY CERTAIN POLARISING SUBSTANCES

In my paper " On the Polarisation of Electric Rays by Double-refracting Crystals " and in a subsequent paper " On a New Electro-Polariscope ", I have given accounts of the polarising property of various substances. Amongst the most efficient polarisers may be mentioned nemalite and chrysotile. Nemalite is a fibrous variety of brucite. In its chemical composition it is a hydrate of magnesia, with a small quantity of protoxide of iron and carbonic acid. This substance is found to strongly absorb electric vibrations parallel to its length, and transmit those that are perpendicular to the length. I shall distinguish the two directions as the directions of absorption and transmission. Chrysotile is a fibrous variety of serpentine. In chemical composition it is a hydrous silicate of magnesia. Like nemalite, it also exhibits selective absorption, though not to the same extent. The transmitted vibrations are perpendicular, and those absorbed parallel to the length. Different varieties of these substances exhibit the above property to a greater or less extent. I have recently obtained a specimen of chrysotile with a thickness of only 2·5 cm.; this piece completely polarises the transmitted electric ray by selective absorption.

The action of these substances on the electric ray is thus similar to that of tourmaline on light. It may be mentioned here that I found tourmaline to be an inefficient polariser of the electric ray; it does transmit the ordinary and the extraordinary rays with unequal intensities, but even a considerable thickness of it does not completely absorb one of the two rays.

In Hertz's polarising gratings, electric vibrations are transmitted perpendicular to the wires, the vibrations parallel to the wires being reflected or absorbed. Such gratings would be found to exhibit electric anisotropy, the conductivity in the direction of the wires being very much greater than the conductivity across the wires. The vibrations transmitted through the gratings are thus perpendicular to the direction of maximum conductivity, or parallel to the direction of greatest resistance. The vibration absorbed is parallel to the direction of maximum conductivity.

As the nemalite and chrysotile polarised the electric ray by unequal absorption in the two directions, I was led to investigate whether they, too, exhibited unequal conductivities in the two directions of absorption and transmission.

Nemalite, unfortunately, is difficult to obtain; I have, however, in my possession two specimens of which one is fairly large, and I obtained with it strong polarisation effects. The second piece is not as good as the first, and is rather small. I cut from this latter piece a square of uniform thickness, the adjacent sides of the square being parallel to the directions of transmission and absorption respectively. The resistances of equal lengths in the two directions (with the same cross section) were now measured. The resistance in the direction of transmission was found to be 35,000 megohms, and that in the direction of absorption, only 14,000 megohms.

It will thus be seen that the direction of absorption is also the direction of greatest conductivity, and the direction of transmission is the direction of least conductivity.

My anticipations being thus verified, I proceeded to make further measurements with other specimens. From the perfect specimen of nemalite in my possession, I cut two square pieces, A and B. The size of piece A is 2·56×2·56 cm., with a thickness of 1·1 cm.; B is 2·76×2·76×1·2 cm.

For the determination of resistances I used a sensitive Kelvin galvanometer, having a resistance of 7000 ohms. With three Leclanché cells, 1·4 volt each, and an interposed resistance equivalent to 55,524 megohms, a deflection of 1 division in the scale reading was obtained. The table below gives the results of the measurements which I carried out. They clearly show how the difference of absorption in the two directions is related to the corresponding difference in conductivity.

I then proceeded to make measurements with chrysotile. The specimens I could obtain were not very good. I cut two from the same piece, and a third specimen was obtained from a different variety. The ratios of conductivities found in the three specimens were 1 : 10, 1 : 9, and 1 : 4 respectively. In every case the direction of absorption was found to be the direction of maximum conductivity.

A fibrous variety of gypsum ($CaSO_4$), popularly known as satinspar, also exhibits double absorption; and in this case, too, the conductivity in the direction of absorption is found to be very much greater than in that of transmission.

Specimen A.	Deflections.	Resistance between two opposed faces 2·56×1·1 cm. separated by 2·56 cm.	Ratio of the conductivities.
In the direction of transmission.	26	2136 megohms	1 : 13·8
In the direction of absorption.	360	154 ,,	

Specimen B.	Deflections.	Resistance between two opposed faces 2·76×1·2 cm. separated by 2·76 cm.	Ratio of the conductivities.
In the direction of transmission.	28	1983 megohms	1 : 13·4
In the direction of absorption.	370	150 ,,	

One of the strongest polarising substances I have come across is epidote. The crystal I have, is very small in size, and I could not get with it complete absorption of one of the two rays. But it exhibits very strong depolarisation effect, even with a thickness as small as 0·7 cm. This is, undoubtedly, due to strong selective absorption in one direction. I cut a square from this crystal 0·7×0·7 cm. with a thickness of 0·4 cm. Using an E. M. F. of 14 volts the deflections obtained (proportional to the two conductivities) were 105 and 20 divisions respectively. The conductivities in the two directions

are, therefore, in the ratio of 5·2 : 1. With an E. M. F. of 100 volts and a diminished sensibility of the galvanometer, the deflections were 205 and 40, the ratio of the conductivities being as 5·1 : 1.

It would thus appear that substances like nemalite which polarise by double absorption, also exhibit double conductivity. It is probable that, owing to this difference of conductivity in the two directions, each thin layer unequally absorbs the incident electric vibrations; and that by the cumulative effect of many such layers, the vibrations which are perpendicular to the direction of maximum conductivity are alone transmitted, the emergent beam being thus completely polarised.

It should, however, be borne in mind that the selective absorption exhibited by a substance depends, also on the vibration frequency of the incident radiation. I have drawn attention to the peculiarity of tourmaline which does not exhibit double absorption of the electric ray to a very great extent. The specimen I experimented with is, however, one of a black variety of tourmaline, and not of the semi-transparent kind generally used for optical work.

Though the experiments already described are not sufficiently numerous for drawing a general conclusion as to the connection between double absorption attended with polarisation, and double conductivity, there is, however, a large number of experiments I have carried out which seem to show that a double-conducting structure does, as a rule, exhibit double absorption and consequent polarisation. Out of these experiments I shall here mention one which may prove interesting. Observing that an ordinary book is unequally conducting in the two directions—parallel to and across the pages—I interposed it, with its edge at 45°, between the crossed polariser and analyser of an electro-polariscope. The extinguished field of radiation was immediately restored. I then arranged both the polariser and the analyser vertical and parallel, and interposed the book with its edge parallel to the direction of electric vibration. The radiation was found completely absorbed by the book, and there was not the slightest action on the receiver. On holding the book with its edge at right angles to the electric vibration, the electric ray was found copiously transmitted. An ordinary book would thus serve as a perfect polariser of the electric ray. The vibrations parallel to the pages are completely absorbed, and those at right angles transmitted in a perfectly polarised condition.

(*Proc. Roy. Soc., Jan.* 1897.)

IX

ELECTRO-MAGNETIC RADIATION AND THE POLARISATION OF THE ELECTRIC RAY

The work of Hertz in verifying the anticipations of Maxwell has been followed in this country by many important investigations on Electric Waves. The Royal Institution witnessed the repetition of some of the brilliant experiments of Professors Fitzgerald and Lodge. I am glad to have an opportunity to lay before you, at this very same place, an account of some work which I carried out in India.

As the subject of ether waves produced by periodic electric disturbances is to be dealt with in this lecture, a few models exhibiting the production of material waves by periodic mechanical disturbances may be of interest. A pendulum swings backwards and forwards at regular intervals of time; so does an elastic spring when bent and suddenly released. These periodic strokes produce waves in the surrounding medium; the aerial waves striking the ear may, under certain conditions, produce the sensation of sound. The necessary condition for audibility is, that the frequency of vibration should lie within certain limits.

As the air is invisible, we cannot see the waves that are produced. Here is a model in which the medium is thrown into visible waves by the action of periodic disturbances. The beaded string representing the medium is connected at its lower end with a revolving electric motor. The rotation of the motor is periodic; observe how the periodic rotation throws the string into waves; how these waves carry energy from the source to a distant place; how a suitable receiver, a bell for example, is made to respond at the distant end. I now produce a quicker rotation by sending a stronger current through the motor; the frequency or pitch is raised, and the waves formed are seen to become shorter. The different frequencies are determined by means of the attached counter.

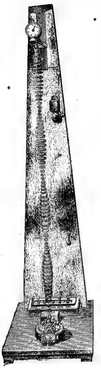

Fig. 16. Mechanical Wave Apparatus.
(The current regulating the speed of rotation is varied by an interposed rheostat. The counter is at the top.)

Here is a second model, a spiral spring, attached to which is a thin string. As the string is pulled, the spring is strained more and more, till the thread breaks. The spring, suddenly released, is seen to oscillate up and down. Electric vibration is produced in a somewhat similar way. If two metallic spheres be strongly charged with opposite electrifications, the medium is electrically strained, and when this strain is suddenly removed by a discharge, waves are produced in the medium.

The discharge is oscillatory, consisting of backward and forward rushes of electricity; positive electricity flowing now in one direction, and immediately afterwards in an opposite direction.

For the production of oscillatory discharge, Hertz used plates or rods with sparking balls at the ends. He found that the sparks ceased to be oscillatory as soon as the surface of the sparking balls became roughened; there was then a leak of electricity, and no sudden discharge. The balls had to be taken out every now and then for repolishing, and the process was tedious in the extreme. Prof. Lodge made the important discovery that if two side balls were made to spark into an interposed third ball, the oscillatory nature of the discharge was not affected to so great an extent by a change in the nature of the surface. But even here the disintegration of the sparking surface produced by a torrent of sparks soon puts an end to oscillation. I found this difficulty removed by making the balls of platinum, which resists the disintegrating action. I also found that it was not at all necessary to have a series of useless sparks, which ultimately spoils the efficiency of the radiator and makes its action uncertain. A flash of radiation for an experiment is obtained from a single spark, and for a series of experiments one does not require more than fifty or a hundred sparks, which do not in any way affect the radiator. As an electric generator I use a small and modified form of Ruhmkorff's coil, actuated by a single storage cell. A spark is produced by a short contact and subsequent break of a tapping key. With these modifications one of the most troublesome sources of uncertainty is removed. The coil and the cell are enclosed in a small double-walled metallic box, with a tube for the passage of the electric beam. The magnetic variation due to the make and break of the primary of the Ruhmkorff's coil, disturbs the receiver. This difficulty is removed by making the inner box of soft iron which acts as a magnetic screen.

A few words may here be said about the necessary conditions to be kept in view in making an electric wave apparatus an instrument of precision. If one merely wishes to produce response in a receiver at a distance, the more energetic the vibration is, the more likely it is to overcome obstacles. The waves may with advantage be of large size, as they possess very great penetrative power. The surface or the depth of the sensitive layer in the receiver may be extended, for if one part of it does not respond another part will. But for electro-optical investigations the conditions to be fulfilled are quite different. Too great an intensity of radiation makes it almost impossible to prevent the disturbance due to stray radiation. As the waves are invisible, it is difficult to know through what unguarded points they are escaping. They may be reflected by the walls of the room or even by the person of the experimenter, and falling on the receiver disturb it.

The radiation falling on any portion of the receiving circuit, the leading wires or the galvanometer, disturbs the sensitive receiver. It is extremely difficult to shield the receiving circuit from the disturbing action of stray radiation. All difficulties were, however, successfully removed by the use of short electric waves. With these, it is not at all necessary to take special precautions to shield either the galvanometer or the leading wires, the sensitive layer in the receiver alone being affected by the radiation. The bare leading wires may be exposed in close proximity to the source of radiation, and yet no disturbance is produced.

For experimental investigations it is also necessary to have a narrow pencil of electric radiation, and this is very difficult to obtain, unless waves of very short length are used. With large waves diverging in all directions and curling round corners, all attempt at accurate work is futile. For angular measurements it is necessary to direct the electric beam in the given direction along narrow tubes, and receive it in another tube in which is placed the receiver. The waves experience great difficulty in passing through narrow apertures, and there are other troubles arising from the interference of direct and reflected waves. All these drawbacks were ultimately removed by making suitable radiators emitting very short waves; the three radiators here exhibited, give rise to waves which are approximately $\frac{1}{4}$ inch, $\frac{1}{2}$ inch and 1 inch in length. The intensity of emitted radiation is moderately strong, and this is an advantage in many cases. It sometimes becomes necessary to have a greater intensity without the attendant trouble inseparable from too long waves. I have been able to secure this by making a radiator, where the oscillatory discharge takes place between two hollow hemispheres and an interposed platinum ball. The intensity of radiation is by this expedient very greatly increased. The parallel pencil of electric radiation, used in many of the experiments to be described below, is only about one cm. in diameter. The production of such a narrow pencil became absolutely necessary for a certain class of investigations. Merely qualitative results for reflection or refraction may no doubt be obtained with gigantic mirrors or prisms, but when we come to study the phenomena of polarisation as exhibited by crystals, Nature imposes a limit, and this limitation of the size of the crystals has to be accepted in conducting any investigation on their polarising properties.

The greatest drawback, however, in conducting experimental investigations on the optical properties of electric radiation arises from the difficulty of constructing a satisfactory receiver for detecting the radiation. For this purpose I at first used the original form of coherer made of metallic filings as devised by Professor Lodge. It is a very sensitive detector for electric radiation, but unfortunately its indications are often extremely capricious.

The conditions for a satisfactory receiver are the following :—

(1) Its indications should always be reliable.
(2) Its sensitiveness should remain fairly uniform during the course of the experiment.
(3) The sensibility should be capable of variation, to suit different experiments.
(4) The receiver should be of small size, and preferably linear, for accurate angular measurements.

These conditions seemed at first almost impossible to attain; the coherer sometimes would be so abnormally sensitive that it would react without any apparent cause. At other times, when acting in an admirable manner, the sensitiveness would suddenly disappear at the most tantalising moment. It was a dreary experience when the radiator and the receiver failed by turns, and it was impossible to find out which was really at fault.

From a series of experiments carried out to find the causes of the erratic behaviour of the receiver, I was led to suppose that the uncertainty in its response is probably due to the following :—

(1) Some of the particles of the coherer might be in too loose a contact against each other, whereas others might be jammed together, preventing proper response.
(2) The loss of sensibility might also be due to the fatigue produced on the contact surfaces by the prolonged action of radiation.
(3) Since the radiation was almost entirely absorbed by the outermost layer, the inner mass, which acted as a short circuit, was not merely useless but might introduce complications.

For these reasons I modified the receiver into a spiral-spring form. Fine metallic wires (generally steel, occasionally others, or a combination of different metals) were wound in narrow spirals and laid in a single layer on a groove cut in ebonite, so that the spirals could roll on a smooth surface. The spirals are prevented from falling by a glass slide in front. The ridges of the contiguous spirals made numerous and well-defined contacts, about one thousand in number. The useless conducting mass was thus abolished, and the resistance of the receiving circuit almost entirely concentrated at the sensitive contact surface exposed to radiation. If any change of resistance, however slight, took place at the sensitive layers, the galvanometer in circuit would show strong indications. The pressure throughout the mass was made uniform as each spring transmitted the pressure to the next. When the contact surfaces had too long been acted on, fresh surfaces could easily be brought into operation by the simultaneous rolling of all the spirals.

The sensibility of the receiver to the radiation, I found, depends (1) on the pressure to which the spirals are subjected, and (2) on the E. M. F. acting on the circuit. The pressure on the spirals may be adjusted, as will be described later on, by means of a fine screw. The E. M. F. is varied by a potentiometer-slide arrangement. This is a matter of great importance, as I often found a receiver, otherwise in good condition, failing to respond when the E. M. F. varied slightly from the proper value. The receiver, when subjected to long-continued radiation, undergoes exhaustion. The sensibility can, however, be maintained fairly uniform by slightly varying the E. M. F. to keep pace with the fatigue produced.

The receiving circuit thus consists of a spiral-spring coherer, in series with a voltaic cell and a dead-beat galvanometer. The spirals are placed between two pieces of brass, of which the upper one is sliding and the lower one fixed. These two pieces are in connection with two projecting metallic rods, which serve as electrodes. An electric current enters along the breadth of the top spiral and leaves by the lowest spiral, having to traverse the intermediate spirals along the numerous points of contact. When electric radiation is absorbed by the sensitive surface, there is a sudden diminution of the resistance, and the galvanometer spot is violently deflected.

By means of a very fine screw the upper sliding piece can be gently adjusted in or out. The spirals can thus be very gradually compressed, and the resistance of the receiver diminished. The galvanometer spot can thus easily be brought to any convenient position on the scale. When electric radiation falls on the sensitive surface the spot is suddenly deflected.

The receiver thus constructed is perfectly reliable; the sensibility can be widely varied to suit different experiments, and this sensibility can be maintained fairly uniform. The sensitiveness, when necessary, can be exalted to almost any extent, and it is thus possible to carry out some of the most delicate experiments (specially on polarisation) with certainty. In my more recent apparatus I use a single-contact receiver made of steel, nickel, aluminium or magnesium. These receivers can not only be made extremely sensitive, but also highly reliable.

The main difficulties having been thus removed, I attempted to construct a portable apparatus, with which all the experiments on electric radiation could be carried out with almost as great an ease and certainty as corresponding experiments on light, and with which even quantitative results could be obtained with fair accuracy.

The complete apparatus is here exhibited; all its different parts, including the galvanometer, and all the accessories for reflection, refraction, polarisation, and other experiments, are contained in a small case only 60 cm. in length, 30 cm. in height and 30 cm. in breadth. The apparatus can be set up and various adjustments made in the course of a few minutes.

The radiating apparatus is 15×12×7 cm., the size of a small lantern. It contains the coil and a small storage cell; the radiator tube is closed with a thin plate of ebonite to prevent deposit of dust on the radiator. One charge of the cell stores enough energy for numerous experiments. It is always ready for use and requires very little attention. A flash of radiation for an experiment is produced by a single tap and break of the interrupting key.

The radiating apparatus and the receiver are mounted on stands sliding on an optical bench. Experiments are carried out with divergent or parallel beams of electric radiation. To obtain a parallel beam, a lens of sulphur or glass is mounted in a tube. Suitable lenses can be constructed from the accurate determination, which I have been able to make, of the indices of refraction of various substances for the electric ray, by a method which will be described later on. This lens-tube fits on the radiator-tube, and is stopped by a guide when the oscillatory spark is at the principal focus of the lens. The radiator-tube is further provided with a series of diaphragms by which the amount of radiation can be varied.

For experiments requiring angular measurement, a spectrometer-circle is mounted on one of the sliding stands. The spectrometer carries a circular platform, on which the various reflectors and refractors are placed. The platform carries an index, and can rotate independently of the circle on which it is mounted. The receiver is carried on a radial arm (provided with an index), and points to the centre of the circle.

I shall now exhibit some of the principal experiments on electric radiation.

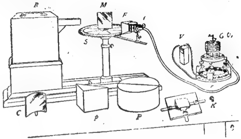

Fig. 17. Arrangement of the Apparatus. One-sixth nat. size.

R, radiator; S, spectrometer-circle; M, plane mirror; C, cylindrical mirror; *p*, totally reflecting prism; P, semi-cylinders; K, crystal-holder; F, collecting funnel attached to the spiral spring receiver; *t*, tangent screw, by which the receiver is rotated; V, voltaic cell; *r*, circular rheostat; G, galvanometer.

Selective Absorption

I arrange the radiation apparatus so that a parallel beam of electric radiation proceeding from the lantern falls on the receiver placed opposite; the receiver responds energetically, the light-spot from the galvanometer being swept violently across the screen. I now interpose various substances to find out which of them allow the radiation to pass through and which do not. A piece of brick, or a block of pitch, is thus seen to be very transparent; whereas a thick stratum of water is quite opaque. A substance is said to be coloured when it allows light of one kind to pass through, but absorbs light of a different kind. A block of pitch is opaque to visible light, but transparent to electric radiation; whereas water, which is transparent to light, is opaque to electric radiation. These substances exhibit selective absorption, and are therefore coloured.

There is an interesting speculation in reference to the possibility of the sun emitting electric radiation. No such radiation has yet been detected in sunlight. It may be that the electric rays are absorbed by the solar or the terrestrial atmosphere. As regards the latter supposition, the experiment which I am able to exhibit on the transparency of liquid air may be of interest. Professor Dewar has kindly lent me this large bulb full of liquid air, which is equivalent to a great thickness of ordinary air. This thick stratum allows the radiation to pass through with the greatest facility, proving the high transparency of the liquid air.

Verification of the Laws of Reflection

A small plane metallic mirror is mounted on the platform of the spectrometer-circle. The receiver is mounted on a radial arm. The law of reflection is easily verified in the usual way. The second mirror, which is curved, forms an invisible image of the source of radiation. As I slowly rotate the cylindrical mirror, the invisible image moves through space; now it falls on the receiver, and there is a strong response produced in the receiver.

Refraction

Deviation of the electric ray can be easily shown by a prism made of sulphur or ebonite. More interesting is the phenomenon of total reflection. A pair of totally-reflecting prisms may be obtained by cutting a cube of glass, which may be an ordinary paper-weight, across a diagonal. The critical angle of a specimen of glass I found to be 29°, and a right-angled isosceles prism of this material produces total reflection in a very efficient manner. When the receiver is placed opposite the radiator, and the prism interposed with one of its faces perpendicular to the electric beam, there is not the slightest action on the receiver. On turning the receiver through 90°, the receiver responds to the totally-reflected ray.

Opacity due to multiple refraction and reflection, analogous to the opacity of powdered glass to light, is shown by filling a long trough with irregularly-shaped pieces of pitch, and interposing it between the radiator and the receiver. The electric ray is unable to pass through the heterogeneous media, owing to the multiplicity of refractions and reflections, and the receiver remains unaffected. But on restoring partial homogeneity by pouring in kerosene, which has about the same refractive index as pitch, the radiation is easily transmitted.

Determination of the Index of Refraction

Accurate determination of the indices of refraction becomes important when lenses have to be constructed for rendering the electric beam parallel. The index for electric radiation is often very different from the optical index, and the focal distance of a glass lens for light gives no clue to its focal distance for electric radiation. I found, for example, the index of refraction of a specimen of glass to be 2·04, whereas the index of the same specimen for sodium light is only 1·53.

There are again many substances, like the various rocks, wood, coal-tar, and others, whose indices cannot be determined owing to their opacity to light. These substances are, however, transparent to electric radiation, and it is therefore possible to determine their electric indices. The prism-method is unsuitable for accurate determination of the index. Very good results are obtained by the following method, of which I shall exhibit the optical counterpart. When light passes from a dense into a light medium, then, at a certain critical angle, the light is totally reflected, and from the critical angle the index can be determined. I have here a cylindrical trough filled with water. Two glass plates enclosing a parallel air-film are suspended vertically across the diameter of the cylinder, dividing the cylinder into two halves. The cylinder, mounted on a graduated circle, is adjusted in front of an illuminated slit, an image of the slit being cast by the water-cylinder on the screen. The divergent beam from the slit, rendered nearly parallel by the first half of the cylinder, is incident on the air-film, and is then focussed by the second half of the cylinder. As the cylinder is slowly rotated, the angle of incidence at the air-film is gradually increased, but the image on the screen remains fixed. On continuing the rotation you observe the almost sudden extinction of the image. I say almost, because the light is not monochromatic, and the different components of white light undergo total reflection in succession. Just before total extinction the image you observe is reddish in colour, the violet and the blue lights having been already reflected. On continuing the rotation the image is completely extinguished. Rotation of the cylinder in an opposite direction gives another reading for total reflection, and the difference of the two readings is evidently equal to twice the critical angle.

In a similar way I have been able to determine the indices of refraction of various substances, both solid and liquid, for electric radiation. In the case of solids, two semi-cylinders, separated by a suitable parallel air-space, are placed on the spectrometer-circle, the receiver being placed opposite the radiator. The trouble of following the deviated ray is obviated, and the critical angle determined with considerable accuracy. The index of refraction of glass thus found is 2·04; that of commercial sulphur, 1·73.

Double Refraction and Polarisation

I now proceed to demonstrate some of the principal phenomena of polarisation, especially in reference to the polarisation produced by crystals and other substances, and by solid dielectrics when subjected to strain due to pressure or unequal heating.

As the wave-length of electric radiation is many thousand times the wave-length of light, there is a

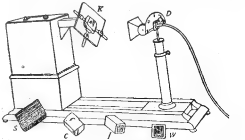

Fig. 18. Polarisation Apparatus.

K, crystal-holder ; S, a piece of stratified rock ; C, a crystal ; J, jute polariser ; W, wire-grating polariser ; D, vertical graduated disc, by which the rotation is measured.

misgiving as to whether it would be possible to exhibit polarisation effects with crystals of ordinary size. I shall demonstrate that such a misgiving is groundless.

A beam of ordinary light incident on a crystal of Iceland spar is generally bifurcated after transmission, and the two emergent beams are found polarised in planes at right angles to each other. The usual optical method of detecting the bi-refringent action of crystal, is to interpose it between the crossed polariser and analyser. The interposition of the crystal at the proper angle brightens the dark field. This is the so-called depolarisation effect, and is a delicate test for double-refracting substances. There is, however, no depolarisation when the principal plane of the crystal coincides with the polarisation planes of either the polariser or the analyser. The field also remains dark when the optic axis of the crystal is parallel to the incident ray.

A similar method is adopted for experimenting with polarised electric radiation.

The spectrometer-circle is removed from the optical bench, and an ordinary stand for mounting the receiver substituted. By fitting the lens-tube, the electric beam is made parallel. At the end of the tube may be fixed either the grating polariser or the jute or serpentine polarisers, to be presently described.

The receiver fitted with the analyser is adjusted by a tangent screw, the rotation of the analyser being measured by means of an index and a graduated vertical disc.

The polarising gratings may be made, according to Hertz, by winding copper wires, parallel, round square frames. The polarisation apparatus is, however, so extremely delicate, that unless all the wires are strictly parallel, and the gratings *exactly* crossed, there is always a resolved component of radiation which acts on the sensitive receiver. It is very difficult to secure the exact crossing of the gratings. I have found it to be a better plan to take two thick square plates of copper of the same size, and, placing one over the other, cut series of slits (which stop short of the edges) parallel to one of the edges. One of these square pieces serves as a polariser, and the other as an analyser. When the two square pieces are adjusted, face to face, with co-incident edges, the gratings must either be parallel or exactly crossed. Such accurate adjustments make it possible to carry out some of the most delicate experiments.

The radiator-tube, with the lens and the attached polariser, is capable of rotation. The emergent beam may thus be polarised in a vertical or a horizontal plane. The analyser fitted on to the receiver may also be rotated. The gratings may thus be adjusted in two positions.

(1) Parallel position.

(2) Crossed position.

In the first position the radiation transmitted through both the gratings, falls on the sensitive surface, and the galvanometer responds. The field is then said to be bright. In the second position the radiation is extinguished by the crossed gratings, the galvanometer remains unaffected, and the field is said to be dark. But the field is restored on interposition of a double-refracting substance in certain positions between the crossed gratings, and the galvanometer-spot sweeps across the scale.

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The analyser and the polariser are now exactly crossed, and there is not the slightest action on the receiver. The polariser is now slightly displaced from the crossed position, and the galvanometer-spot is seen to be violently deflected.

The gratings are once more adjusted in a crossed position. I have in my hand a large block of the crystal beryl which is perfectly opaque to light. I now hold the crystal with its principal plane inclined at 45° between the crossed gratings, and the galvanometer-spot, hitherto quiescent, sweeps across the scale. It is very curious to observe the restoration of the extinguished field of electric radiation, itself invisible, by the interposition of what appears to the eye to be a perfectly opaque block of crystal. If the crystal is slowly rotated, there is no action on the receiver when the principal plane of the crystal is parallel to either the polariser or the analyser. Thus, during one complete rotation there are four positions of the crystal when no depolarisation effect is produced.

Rotation of the crystal, when held with its optic axis parallel to the incident ray, produces no action. The field remains dark.

Here is another large crystal, idocrase, belonging to the orthorhombic system, which shows the same action. It is not at all necessary to have large crystals ; a piece of calc-spar, taken out of an optical instrument, will be found effective in polarising the electric ray. The effect produced by the crystal epidote is, however, extraordinary. I have here a piece with a thickness of only ·7 cm., smaller than a single wave-length of electric radiation, and yet observe how strong is its depolarising effect.

I subjoin a representative list of crystals belonging to the different systems, which would be found to produce double refraction of the electric ray.

Tetragonal System.—Idocrase, scapolite.

Orthorhombic System.—Barytes, celestine, cryolite, andalusite, hypersthene.

Hexagonal System.—Calcite, apatite, quartz, beryl, tourmaline.

Monoclinic System.—Selenite, orthoclase, epidote.

Triclinic System.—Labradorite, microcline, amblygonite.

Double Refraction produced by a Strained Dielectric

Effect due to Pressure.—A piece of glass, when strongly compressed, becomes double refracting for light. An analogous experiment may be shown with electric radiation. Here is a piece of slate which from the nature of its formation had been subjected to great pressure. I interpose this piece with the plane of stratification inclined at 45°, and the spot of light flies off the scale. I now carefully rotate the piece of slate ; there is no depolarisation effect when the plane of stratification is parallel to either the polariser or the analyser. Thus the existence of strain inside an opaque mass can easily be detected, and what is more, the directions of maximum and minimum pressures can be determined with great exactitude.

An effect similar to that produced by unannealed glass may be shown by this piece of solid paraffin, which was cast in a mould, and chilled unequally by a freezing mixture. One of these blocks was cast two years ago, and it has still retained its unannealed property. This effect may even be shown without any special preparation. Pieces of glass or ebonite, too, are often found sufficiently strained to exhibit double refraction of the electric ray.

Phenomena of Double Absorption

In search of a crystal polariser, I naturally turned to tourmaline, but was disappointed to find it utterly unsuitable as a polariser. There is a difference in transparency in directions parallel and perpendicular to the length, but even a considerable thickness of the crystal did not completely absorb one of the two rays. Because tourmaline polarises visible light by selective absorption, it does not follow that all kinds of radiation would be so polarised.

It was a long time before I could discover crystals which acted as electric tourmalines. In the meanwhile I found many natural substances which produced polarisation by selective unilateral absorption. For example, I found locks of human hair to polarise the electric ray. I have here two bundles of hair; I interpose one at 45°, and you observe the depolarisation effect. The darker specimen seems to be the more efficient. Turning to other substances more easily accessible, I found vegetable fibres to be good polarisers. Among these may be mentioned the fibres of aloes (*Agave*), rhea (*Boehmeria nivea*), pine-apple (*Ananas sativus*), plantain (*Musa paradisiaca*). Common jute (*Corchorus capsularis*) exhibits the property of polarisation in a very marked degree. I cut fibres of this material about 3 cm. in length, and built with them a cell with all the fibres parallel. I subjected this cell to a strong pressure under a press. I thus obtained a compact cell 3 cm. by 3 cm. in area, and 5 cm. in thickness.

This was mounted in a metallic case, with two openings 2 cm. by 2 cm. on opposite sides for the passage of radiation. This cell absorbs vibrations parallel to the length of the fibres, and transmits those perpendicular to the length. Two such cells could thus be used, one as a polariser and the other as an analyser.

Turning to crystals I found a large number of them exhibiting selective absorption in one direction. Of these nemalite and chrysotile exhibit this property to a remarkable extent. Nemalite is a fibrous variety of brucite, chrysotile being a variety of serpentine. The direction of absorption in these cases is parallel to the length, the direction of transmission being perpendicular to the length. I have here a piece of chrysotile, only one inch in thickness. I adjust the polariser and the analyser parallel, and interpose the chrysotile with its length parallel to the electric vibration. You observe that the radiation is completely absorbed, none being transmitted. I now hold the piece with its length perpendicular to the electric vibration; the radiation is now copiously transmitted. Chrysotile is thus seen to act as a perfect electric tourmaline.

Anisotropic Conductivity exhibited by certain Polarising Substances

In a polarising grating, the electric vibrations perpendicular to the bars of the grating are alone transmitted, the vibrations parallel to the grating being absorbed or reflected. In a grating we have a structure which is not isotropic, for the electric conductivity parallel to the bars is very great, whereas the conductivity across the bars (owing to the interruptions due to spaces) is practically zero. We may, therefore, expect electric vibrations parallel to the bars to produce local induction currents, which would ultimately be dissipated as heat. There would thus be no transmission of vibrations parallel to the grating, all such vibrations being absorbed. But owing to the break of metallic continuity, no induction current can take place across the grating; the vibrations in this direction are, therefore, transmitted. From these considerations it is seen how non-polarised vibrations falling on a grating would have the vibration components parallel to the direction of maximum conductivity absorbed, and those in the direction of least conductivity transmitted in a polarised condition.

I have shown that nemalite and chrysotile polarise by selective absorption, the vibration perpendicular to their length being transmitted, and those parallel to their length being absorbed. Bearing in mind the relation between the double conductivity and double absorption, as exhibited by gratings, I was led to investigate whether the directions of the greatest and least absorptions in nemalite and chrysotile were also the directions of maximum and minimum conductivities respectively. I found the conductivity of a specimen of nemalite in the direction of absorption to be about fourteen times the conductivity in the direction of transmission. In chrysotile, too, the directions of the greatest and least absorption were also the directions of maximum and minimum conductivities.

It must, however, be noted that the substances mentioned above are bad conductors, and the difference of conductivity in the two directions is not anything like what we get in polarising gratings. A thin layer of nemalite or chrysotile will, therefore, be unable to produce complete polarisation. But by the cumulative effect of many such layers in a thick piece, the vibrations which are perpendicular to the direction of maximum conductivity are alone transmitted, the emergent beam being thus completely polarised.

A double-conducting structure will thus be seen to act as a polariser. I have here an artificial electric tourmaline, made of a bundle of parallel capillary glass fibres. The capillaries have been filled with dilute copper sulphate solution.

A simple, and certainly the most handy, polariser is one's outstretched fingers. I interpose my fingers at 45° between the crossed polariser and the analyser, and you observe the immediate restoration of the extinguished field of radiation.

While repeating these experiments I happened to have by me this old copy of 'Bradshaw', and it occurred to me that here was an excellent double-conducting structure which ought to polarise the electric ray. For looking at the edge of the book we see the paper continuous in one direction along the pages, whereas this continuity is broken across the pages by the interposed air-films. I shall now demonstrate the extraordinary efficiency of this book as an electric polariser. I hold it at 45° between the crossed gratings, and you observe the strong depolarisation effect produced. I now arrange the polariser and the analyser in a parallel position, and interpose the 'Bradshaw' with its edge parallel to the electric vibration; there is not the slightest action in the receiver, the book held in this particular direction being perfectly opaque to electric radiation. But on turning it round through 90°, the 'Bradshaw', usually so opaque, becomes quite transparent, as is indicated by the violent deflection of the galvanometer-spot of light. An ordinary book is thus seen to act as a perfect polariser of the electric ray; the vibrations parallel to the pages are completely absorbed, and those at right angles transmitted in a perfectly polarised condition.

The electric radiation is thus seen to be reflected, refracted and polarised just in the same way as light is reflected, refracted and polarised. The two phenomena are identical.

By pressing the key of this radiation apparatus I am able to produce ether vibrations 30,000 millions in one second. A second stop in connection with another apparatus will give rise to a different vibration. Imagine a large electric organ provided with a very large number of stops, each key giving rise to a particular ether note. Imagine the lowest key producing one vibration in a second. We should then get a gigantic ether wave 186,000 miles long. Let the next key give rise to two vibrations in a second, and let each succeeding key produce higher and higher notes. Imagine an unseen hand pressing the different keys in rapid succession. The ether notes will thus rise in frequency from one vibration in a second, to tens, to hundreds, to thousands, to hundreds of thousands, to millions, to millions of millions. While the ethereal sea in which we are all immersed is being thus agitated by these multitudinous waves, we shall remain entirely unaffected, for we possess no organs of perception to respond to these waves. As the ether note rises still higher in pitch, we shall for a brief moment perceive a sensation of warmth. As the note still rises higher, our eye will begin to be affected, a red glimmer of light will be the first to make its appearance. From this point the few colours we see are comprised within a single octave of vibration, from about 400 to 800 billions in one second. As the frequency of vibration rises still higher, our organs of perception fail us completely; a great gap in our consciousness obliterates the rest. The brief flash of light is succeeded by unbroken darkness.

These great regions of invisible lights are now being slowly and patiently explored. In time the great gaps which now exist will be filled up, and light-gleams, visible and invisible, will be found merging one into the other in unbroken sequence.

Before concluding I take this opportunity of expressing my sincere thanks to the Managers of the Royal Institution for according me the privilege of addressing you this evening. The land from which I come did at one time strive to extend human knowledge, but that was many centuries ago. It is now the privilege of the West to lead in this work. I would fain hope, and I am sure I am echoing your sentiments, that a time may come when the East, too, will take her part in this glorious undertaking; and that at no distant time it shall neither be the West nor the East, but both the East and the West, that will work together, each taking her share in extending the boundaries of knowledge, and bringing out the manifold blessings that follow in its train.

(Friday Evening Discourse, Royal Institution, Jan. 1897.)

X

THE ROTATION OF PLANE OF POLARISATION OF ELECTRIC WAVES BY A TWISTED STRUCTURE

In my previous papers I have given accounts of the double refraction and polarisation of electric waves produced by various crystals and other substances, and also by strained dielectrics. An account was there given of the polarisation apparatus with which the effects were studied. In the present investigation effects had to be studied which were exceedingly feeble. The apparatus had, therefore, to be made of extreme sensitiveness; but the secondary disturbances became at the same time more pronounced, and the great difficulty experienced was in avoiding them.

In one of my communications I alluded to the fact that the secondary disturbances are to a great extent reduced when the radiators are made small. The advantage of a large radiator is the comparative ease with which the receiver can be adjusted to respond to the waves, but this advantage is more than counterbalanced by the increased difficulty with the stray radiation and other disturbances. On the other hand, with small radiators, the difficulty is in the proper adjustment of the receiver. It then becomes necessary to have very exact adjustments of the receiver, both as regards the pressure to which the sensitive spirals are subjected and the E. M. F. acting on the circuit. It is only after some practice that the peculiarity of each receiver is properly understood, when it becomes easy to make the necessary adjustments by which the receiver

becomes quite certain in action. For various reasons the radiation emitted by small radiators are more favourable for accurate work.

In order that the surface of the radiator should be little affected by the disintegrating action of the sparks, I use a single spark for producing a flash of radiation. There used to be, however, some uncertainty from a discharge occasionally failing to be oscillatory. The cause of this uncertainty is ascribed to the deposit of dust on the sparking surface. For greater certainty of action some observers immerse the radiator in oil. The use of oil is under any circumstances troublesome. This is specially so in polarisation experiments, when the radiator has to be placed in different azimuths. I have for these reasons avoided the oil-immersion arrangement, and have tried to secure certainty of oscillatory discharge without this expedient. Attention was specially paid to the coil and the primary break. A radiator has also been constructed which is found to be extremely efficient. It consists of two platinum beads, each 2 mm. in diameter, separated by 0·3 mm. spark-gap. There is no interposed third ball. This radiator, though kept exposed for days without any protecting cover, was yet found to give rise to a succession of effective discharges without a single failure. I even went so far as to pour a stream of dust on the radiator; in spite of this severe treatment, the sparks were found to be quite effective in giving rise to electric oscillation.

The receiver, too, is perfectly certain in its action, and various degrees of sensitiveness may be given to it. In the following experiments, the sensitiveness had to be very greatly enhanced, and this, as alluded to above, was secured by proper adjustments. The secondary disturbances were got rid of by careful screening. But one serious difficulty was encountered at the very outset, in the failure of the polariser to produce *complete* polarisation. In my first experiments on polarisation (the receiver then used not having been very sensitive), polarisers made of wire gratings were found effective. But in my later experiments with still more sensitive receivers, I found that, owing probably to the want of strict parallelism of the wires and the difficulty of *exactly* crossing the analyser and polariser, it was impossible to produce total extinction of the field. I then made a polariser and analyser by cutting parallel slits out of two square pieces of thick copper. When the square pieces were adjusted with coincident edges, the analyser and polariser were either exactly parallel or exactly crossed. This improvement enabled me to carry out successfully some of the more delicate experiments. In the present course of investigation the sensitiveness of the receiver had to be raised to a still higher degree, and it was found that the polariser hitherto found efficient failed to produce complete polarisation, so that even when the polariser and the analyser were exactly crossed the non-polarised portion of radiation was of sufficient intensity to produce strong action on the receiver.

In the paper "On the Selective Conductivity exhibited by some Polarising Substances" I described a book-form of polariser, when an ordinary book was shown to produce polarisation of the transmitted beam, the vibrations parallel to the pages being absorbed, and those at right angles transmitted in a polarised condition. The advantage of this form of polariser was that

the extent to which the rays were polarised depends on the thickness of the polarising medium. The rays could thus be completely polarised by giving the medium a sufficient thickness, this thickness being determined by the intensity of the radiation used and the sensitiveness of the receiver. The necessary thickness of the book-polariser can be materially decreased by making the book consist of alternate leaves of paper and tinfoil. The book was then strongly compressed, and blocks of suitable size cut out to form the polariser and the analyser. Each of these blocks is then enclosed in a brass cell, with two circular openings on opposite sides for the passage of radiation. The size of the polariser I use is 6×6 cm., with a thickness of 4·5 cm.; the aperture is 4 cm. in diameter. These polarising cells I find to be quite efficient; when two such cells are crossed, the field is completely extinguished.

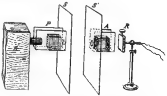

Fig. 19. Polarisation apparatus. B, the radiating box; P, the polariser; A, the analyser; S, S′, the screens; R, the receiver.

The diagram explains the general arrangement of the apparatus, mounted on an optical bench. The spark gap of the radiator is horizontal. The polariser, with the leaves vertical, is placed on a shelf attached to a screen of thick brass plate 35×35 cm. In the centre of the plate there is a circular opening 4 cm. in diameter; this aperture may be varied by a series of diaphragms. There is a second similar screen with a shelf for the analyser, which is placed with the leaves horizontal. Behind the analyser is the receiver.

In the space between the brass plates is placed the substance to be examined. Previous tests are made to see whether all disturbing causes have been removed. The sensitiveness of the receiver is occasionally tested by interposing one's finger at 45° between the crossed polariser and analyser; this should, by partially restoring the field, produce strong action, provided the receiver is in a fairly sensitive condition.

Care should be taken that there are no metallic masses between the screens, as reflection from metals is found to produce " depolarisation ", the rays being then elliptically polarised. The substance to be examined should not, for very delicate experiments, be held by the hand, owing to the disturbing action of the fingers. It is preferable to have the substances supported on stirrups made of thin paper. The above are some of the main precautions to be taken in carrying out the following experiments, where the effects to be detected are very small and therefore likely to be masked unless all disturbing causes are carefully excluded.

I have in a previous communication made mention of the double refracting property of fibrous substances like jute. The field is restored when a bundle of jute is placed at 45° between the crossed polariser and analyser. There is, however, no depolarisation effect when the axis of the bundle is parallel to the direction of the ray.

I now took three similar bundles, A, B and C, of parallel fibres of jute 10 cm. in length and 4·5 cm. in diameter. No change was made in the bundle A which was kept as a test one. The bundles B and C were then twisted, B in a right-handed direction and C in a left-handed direction.

The interposition of the untwisted bundle A between the crossed polariser and analyser did not produce any effect, but strong action was produced in the receiver when the bundles, twisted to the right or to the left, were so interposed. It thus appeared as if the twisted structures produced an optical twist of the plane of polarisation.

Further experiments to be described below may be of some interest in connection with the optical rotation produced by liquids. Here two different classes of phenomena may be distinguished :—

(1) The rotation induced by magnetic field; this rotation among other things is dependent on the direction and intensity of the magnetic field, and is doubled when the ray is reflected back.

(2) The rotation produced by saccharine and other solutions, when the rotation is equal in all directions and simply proportional to the quantity of active substance traversed by the ray; the rotation in this case is neutralised when the ray is reflected back.

The difficulties in the way of explaining rotation produced by liquids are summarised in the following extract :—

" It is, perhaps, not surprising that crystalline substances should, on account of some special molecular arrangement, possess rotatory power, and affect the propagation of light within the mass in a manner depending on the direction of transmission. The loss of this power when the crystalline structure is destroyed, as when quartz is fused, is consequently an event which would be naturally expected, but the possession of it in all directions by fluids and solutions, in which there cannot be any special internal arrangement of the mass of the nature of a crystalline structure, is not a thing which one would have been led to expect beforehand. To Faraday it appeared to be a matter of no ordinary difficulty; it is just possible that the light, in traversing a solution in which the molecules are free to move, may, on account of some peculiarity of structure, cause the molecules to take up some special arrangement, so that the fluid becomes as it were polarised by the transmission of the light, in a manner somewhat analogous to that in which a fluid dielectric is polarised in a fluid of electrostatic force."*

In order to imitate the rotation produced by liquids like sugar solutions, I made small elements or "molecules" of twisted jute, of two varieties, one kind being twisted to the right (positive) and the other twisted to the left (negative). I now interposed a number of, say, the positive variety, end to end, between the crossed polariser and analyser; this produced a restoration of the field. The same was the case with the negative variety. *I now mixed equal numbers of the two varieties, and there was now no restoration of the field, the rotation produced by one variety being counteracted by the opposite rotation produced by the other.*

To get complete neutralisation, it is necessary that the element should be of the same size, and that the two varieties should be twisted (in opposite directions) to the same amount. The experiment was repeated in the following order, to avoid any uncertainty due to the possible variation of the sensitiveness of the receiver. The receiver is adjusted to a particular sensitiveness, and as long as it is not disturbed by the action of radiation, the sensitiveness remains constant. A mixture of opposite elements is first interposed, the receiver continuing to remain unaffected. From the mixture of positive and negative varieties, one set, say the negative, is now rapidly withdrawn, and an equal number of positive substituted. The receiver which has not been disturbed since its first adjustment is now found to respond, all the elements conspiring to produce rotation in the same direction. It will be seen that the two experiments are carried out under identical conditions.

In the above, we have electro-optic analogues of two varieties of sugar—dextrose and levulose. There is also the production of an apparently inactive variety by the mixture of two active ones.

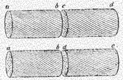

Fig. 20. Jute elements.

It is to be noted that there is no polarity in the elements, in the sense we use the term in reference to, say, magnetic molecules. *There is nothing to distinguish, one end of the jute element from the other end; indeed a right-handed element would appear right-handed when*

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* Preston, 'On Light,' 2nd ed., p. 421.

looked at from either end. It thus happens that if the rotation is determined by the direction of the twist, two molecules of the same variety will always conspire whether they are arranged as *ab*, *cd*, or, to take the extreme case, as *ab*, *dc* (with the second molecule reversed). The assumption of any particular arrangement of molecules is thus not necessary in explaining the rotation. The average effect produced by a large number of active elements interspersed in an inactive medium will thus be the same in all directions, and proportional to the number of molecules traversed by the ray. *As there is no polarity in the molecule*, a right-handed element will always produce the same kind of rotation, say, to the right of an observer travelling with the ray. The rotation produced when the ray is reversed by reflection will thus be in an opposite direction, and the two rotations will neutralise each other.

But if the molecules exhibit any polarity, that is to say, if the effects produced by the two ends of the same molecule are opposite, the resultant effect produced by a number of such molecules arranged in haphazard directions, will be zero. In order that the effects produced by the molecules may conspire, it is necessary that they should take up a special arrangement like the disposition of molecules in a magnetised rod. It is seen that in this case the rotations of the direct and the reflected rays are in the same direction, and the resultant rotation is therefore doubled. There is some analogy between the action of such polarised molecules and of substances which, when placed in a magnetic field, rotate the plane of polarisation.

(*Proc. Roy. Soc., Mar.* 1898.)

XI

ON THE PRODUCTION OF A "DARK CROSS" IN THE FIELD OF ELECTRO-MAGNETIC RADIATION

A circular piece of chilled glass when interposed between crossed Nicols produces a dark cross. A similar effect is produced by crystals like salicine where there is a radial disposition of the principal planes.

I have been able to detect a similar phenomenon in the field of electric radiation by the interposition of an artificial structure between the crossed polariser and analyser.

I have in a previous communication described the polarisation produced by the leaves of a book. For the following experiment, a long strip of paper was rolled into a disc. A roll of Morse's tape serves the purpose very well. The diameter of the disc is 14 cm. and its thickness 2 cm. It will be observed that here we have a single axis passing through the centre, and that all planes passing through the centre are principal planes.

The effect produced by the interposition of the structure may be studied by keeping the disc fixed and exploring the different parts of the field by means of the detector; or the detector may be kept fixed (opposite the analyser) and the disc may be moved about so that the different parts of the field may successively be brought to act on the detector. This latter plan was adopted as being simpler in practice.

The arrangement of the apparatus is the same as in fig. 19 of my previous paper. The polariser is vertical and the analyser horizontal. The paper disc is interposed between the screens with its plane at right angles to the direction of the ray.

The receiver is fixed on the prolongation of the line (which I shall call the *axis*), joining the centres of the polariser and the analyser.

On the supposition that the interposition of the disc produces a dark cross, the arms of the cross (with the particular arrangement of the polariser and the analyser) will lie in the projections of the vertical and the horizontal diameters of the disc, and will move in space with the movements of the disc. When the centre of the disc is on the axis, the intersection of the cross will be superposed on the receiver, and there should then be no action. If the disc be moved up and down, the centre remaining in the vertical line passing through the axis, the vertical arm of the cross will slide over the receiver. If the disc be moved laterally, with its centre in the horizontal line passing through the axis, the horizontal arm of the cross will slide over the receiver. In this, as in the last case, there should be no action on the receiver. But if the disc be displaced so that the centre does not lie in either the horizontal or the vertical line passing through the axis (the axis now cutting the disc at points such as *a*, *b*, *c* or *d*), the arms of the cross will not fall on the receiver, and there should be a response in the receiver (see fig. 21).

The experiments were now arranged as follows :— The disc was at first placed with its centre on the axis, the plane of the disc being perpendicular to the axis. There was now no action on the receiver; but as soon

as the disc was tilted, however slightly, an action was immediately produced on the receiver.

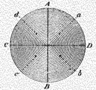

Fig. 21. The paper disc. AB, CD are the vertical and horizontal diameters.

The disc was now mounted on a stand, between the two screens. By means of sliding arrangements the disc could be raised or lowered, or moved laterally.

In the next experiment, the centre of the disc was first adjusted on the axis, and the disc moved vertically up and down. No effect was produced when this was being done.

The centre of the axis was again adjusted on the axis, and the disc moved laterally on the horizontal slide. In this case, too, there was no action.

By adjusting the vertical sliding rod the centre of

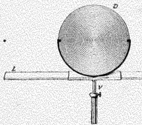

Fig. 22. The holder for the disc. D, the paper disc. V, L are the vertical and horizontal slides.

the disc was next placed vertically above or below the axis. The disc was then moved laterally either to the right or to the left. In this way the field could be displaced, and the quadrants *a*, *b*, *c*, or *d* (*cf.* fig. 21) placed opposite to the receiver. In all these cases, even with small displacements, very strong action was produced on the receiver.

From experiments carried out in the manner described above, the outline of a dark cross projected in space was distinctly made out.

The production of a dark cross can also be demonstrated by interposing between the crossed polariser and analyser concentric rings of tin-foil mounted on a thin sheet of mica. But greater interest is attached to the exhibition of the phenomenon by double refracting substances, where the axes of elasticity are disposed in radial directions. From the peculiar stresses present, I surmised that woody stems with concentric rings would exhibit the phenomenon above described. I experimented with transverse sections of stems of *Pinus longifolia, Swietenia mahogani, Araucaria Cunninghamii, Mangifera indica, Casuarina equisetifolia, Cupressus torulosa* and *Dalbergia sissoo*. The ring systems present in some of these were very regular. I was, however, at first disappointed in failing to obtain the results anticipated. But this failure, I subsequently found, was due to the general opacity of the wood which was freshly cut, and which, though apparently dry, contained large quantities of sap in the interior. I then carefully dried some of the specimens, when the stresses present became quite apparent by numerous cracks starting in radial directions. The results obtained with these dried specimens were quite satisfactory.

I now tried to devise some experiments strictly analogous to the optical experiments with chilled glass. I obtained extremely good results with a cylinder of cast ebonite, in which the stresses present are exactly similar to those in a circular piece of unannealed glass.

The next series of experiments were undertaken with mineral specimens. One very interesting object obtained from Egypt was formed by ringed concretion of flint round a central nodule. This specimen exhibited the cross with great distinctness. I also obtained fairly satisfactory results with stalactite. The concretion of calcium carbonate formed inside a pipe by deposits from temporarily hard water flowing through it, would also be found to exhibit this phenomenon.

(*Proc. Roy. Soc., March* 1898.)